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Optical and Modulation Transfer Functions

Interim Report of ISP Commission I Working Group

Abstract: *The Working Group on Optical and Modulation Transfer Functions is concerned with OTF and MTF standards, with comparative lens testing using OTF techniques, with OTF test equipment and its control, and with evaluation of the quality of aerial and space photography. The status of work within these fields is reported with emphasis on applications.*

Simple and informative control tests using OTF techniques are now routine in lens manufacture. The standards of several nations point out different concepts and different controls. As a result, the Working Group will propose revision of Section 6 of Commission I document "Procedures for Calibrating Photogrammetric Cameras and Related Optical Tests."

The application of MTF techniques to analysis of remote sensing imagery are becoming increasingly important. MTFs derived from aerial and satellite photographs of periodic targets, and artificial and natural edges have been successfully employed to analyze sensor performance and image quality. Comparing these MTFs with laboratory resolution and MTF data for the same camera system, the photogrammetrist can establish resolution values for the operational images. Other photogrammetric and cartographic applications of MTFs or related functions include: analysis of pointing precision and accuracy; quality control studies; and the determination of the fidelity with which image detail can be transferred through the map reproduction process.

A project to assure optimum image quality of aerial photography is being conducted by the US Air Force. All phases of the photographic process are being examined and new standards are being written and/or old ones modified. An Image-Quality Manual is being written which at certain stages requires MTF analyses.

Introduction

History of ISP Activity in Optical and Modulation Transfer Functions (MTF)

The first significant work of Commission I (Primary Data Acquisition, the International Society of Photogrammetry (ISP) on Optical Transfer Functions OTF covering many years of study was reported by Brock,[1] Chairman of the Working Group on Image Quality at the 1968 ISP Congress. That report presented the theory of transfer functions, methods of measuring photogrammetric lenses, and general applications in aerial photography. The results of an interlaboratory test (of a 12-inch, f/4 lens) in which eight laboratories in four nations (West Germany, England, Sweden and the United States) participated showed a spread in MTF values both on-axis and at 15° off-axis, the later as high as 30 percent. Although the study could not include an analysis of the cause of the differences, it greatly emphasized the need for a study of measuring errors and a means for controlling them.

* Presented at ISP Symposium, Comm. I, Stockholm, August 1974. Mrs. Norton served as Secretary of Comm. I 1968-1972.

A section on transfer-function measurement was written for inclusion in the ISP document "Recommended Procedures for Calibrating Photogrammetric Cameras and Related Optical Tests." This became Section 6 on Congress recommendation.

The work on transfer functions continued during the 1968-72 quadrennium, primarily under Welender. His report[2] to the 1972 Congress covered theory, MTFs of film and the proposed U.S. standard for film MTF, current work on MTF and application to aerial photography. His working group recommended continuation of OTF and MTF studies. Norton[3] organized a panel on OTF standards submitting a report based on international answers to a questionnarie that showed the complex problems associated with drafting an ISP standard. The majority opinion was that a standard was not yet timely. Correlating between laboratories showed improvement (1972) but significant variables still existed on off-axis results. Hopkins and Dutton[4] reported that different design programs also gave different MTF data.

Present Status.

At this date (1974) there is increasing emphasis on problems of partial coherence, noise, and the evaluation of phase. Interferometric methods are recommended as being more accurate, complex scanning equipment and complicated programs are being employed.

As the studies on transfer functions accumulate one becomes increasingly aware of the boundary conditions that limit and define the test techniques, the test equipment, and the devices to which they can be applied. If ISP standards are to be written, it is not feasible to limit them to photogrammetric lenses, nor to limit the test equipment and avoid techniques which are most diverse.

Proposal for Section 6.

The Working Group therefore proposes to rewrite or modify Section 6 of the "Recommended procedures for Calibrating Photogrammetric Cameras and Related Optical Tests" with the purpose of showing MTF and OTF as a means of stating the performance of lenses in a which which can be universally understood. The test result should be capable of being reproduced on different apparatus, of different design or priniciple. It is expected that the precautions to assure accuracy and the basic definition will be included in the document. To assist the general readers, selected references to national or international standards, expanded definitions, tutorial reviews, etc., will be included.

Preliminary Conclusions and Recommendations.

Proposals concerning a standard.

a. As explained in the previous paragraphs, it is not advisable to produce a pure standard.
b. The working group proposes to present a new edition of the present Section 6 of the ISP "Recommended Procedures . . . ."
c. The additions and/or modifications to Section 6 will include:

(1) Basic definitions.

(2) Methods of testing (none specifically recommended).

(3) Precautions or limitation of the equipment and techniques.

(4) Calibration tests of test equipment.

(5) Photo cell performance referenced to spectral characteristics of selected or standard film.

(6) Light source — white (mean sun) and one or more narrow band, preferably 525 nm.

(7) Testing of cameras — physical requirements.

System testing.

The ability to locate and measure images for photogrammetric purposes depends primarily on their quality. Studies should be continued tying together location and measurability as a function of modulation and phase.

The 1972 Congress Resolution. The second resolution of Commission I of the XII Congress (August 1972) reads as follows:

"Commission I has found that the results of the various Optical Transfer Functions (OTF) testing methods are not in sufficient agreement to permit the development of an OTF standard. However, because OTF has been demonstrated to be a scientific tool for evaluating the image quality of lenses, it is recommended that appropriate studies, investigations, and correlation testing of OTF continue.

"Furthermore, in accordance with the findings and suggestions of the working group on Modulation Transfer Functions (MTF), Commission I recommends continuation of this activity, including establishment of specifications and tolerances for test equipment and quality assessment of imagery." The previous paragraphs recommend continued studies by this working group.

Correlation Testing. The most extensive correlation testing is that recently conducted by SIRA[6] A paper covering this testing was presented at the Symposium in Sweden (August 1974). Correlation testing should be continued until such time as agreement is satisfactory or causes of disagreement can be isolated.

The OTF/MTF Working Group

Three people comprise the OTF/MTF Working Group which was organized so that the activity of work within the image-quality field of transfer functions would be reported and further consideration could be given to developing an OTF Standard. Gerald C. Brock has continued his research work on MTF lens testing and evaluation (begun at Itek under contract to the US Air Force[5]) and is presently active in SIRA[6] as well as at Vinton Ltd.[7] where he has introduced MTF in Quality Control. The involvement with SIRA has kept him active on the latest studies in correlated testing and the techniques for calibrating laboratories. He will report on the proposed revision of Section 6 and expects to rewrite that document.

Dr. Roy Welch has been developing MTF analytic techniques for evaluating photographic systems for many years. In his work at Geological Survey he has frequently been involved in the analysis of imagery taken from satellites. Since the image quality of systems determine the quality (and probably quantity) of information of our remote sensors, Welch will keep us informed on world-wide system MTF projects. He is presently professor in the Dept. of Geography at the University of Georiga.

Clarice L. Norton has worked in industry for several decades at Fairchild Camera during which she was involved in determining the photographic performance quality of aerial lenses and cameras, becoming interested in MTF testing when first investigated for the Air Force by Brock (at Itek). Now working in the Maintenance Director's Camera Calibration Facility and still concerned with testing of aerial cameras, she represents the production viewpoint of industry and government. Norton will report on the status of present work as well as the special project on analyzing the imagery of two photogrammetric cameras now being accomplished at Wright-Patterson Air Force Base.

PROGRAM FOR THE WORKING GROUP ON OTM AND MTF

A.0 Standardization
A.1 National Standards
A.2 I S P Proposed Standards
A.3 Tests for Accuracy and Precision

B.0 OTF Testing
B.1 Methods of Testing
B.2 Production Testing
B.3 OTF in Research
B.4 OTF in Lens Design

C.0 System Testing
C.1 Working Group Test at Wright-Patterson Air Force Base
C.2 Space Imagery
C.3 Reports from Nations
C.4 Application to Quality Control

D.0 Current Studies
D.1 Signal to Noise
D.1.1 Significance, Methods of Analysis, Control
D.2 Phase
D.3 Coherence
D.4 Cascading

E.0 Interferometric Methods

F.0 Practical Application
F.1 Aerial Photography — Use of Natural Test Edges
F.2 Cascading of Components
F.3 Coherence Problems

G.0 Recommendations and Proposals.

MTF System Testing for Working Group

Photographs taken by the Canadian Air Force (The Zeiss & Wild cameras being used by Commission I Image Quality Working Group) under Ziemann is now being analyzed at the Dynamics and Environmental Evaluation Branch, Air Force Avionics Laboratory, Wright-Patterson Air Force Base in the United States. Approximately 50 edges will be traced for each camera covering the 23 cm × 23 cm format. In addition to MTF other information will include exposure evenness, granularity, aerial contrast, resolution. A full report will be available at the 1976 Congress in Helsinki.

Standards

A review of the world-wide situation on OTF standards is considered essential to the Working Group studies and the basis for recommendations on standards. This section lists the OTF, MTF, and related standards which are now in use in member nations or are being developed and it discusses the activity associated with the establishment of those standards as contained in private letters of communication and publishings. (It should be noted that this is an interim report and that all national standards are not included at this time.)

Interest in standards began as far back as 1961 when the International Commission on Optics agreed on definitions for Optical, Modulation, and Phase Transfer Functions. Since then other definitions and concepts relating to Optical Transfer Function testing and evaluation have been reviewed and published.

Simultaneous with the development of test equipment and test techniques was the interest in standards which are only useable if tests on different apparatus produce similar results. As correlation testing between laboratories emphasized the differences between test values, testing requirements and test equipment were refined. Today several countries have OTF specifications differing in complexity; yet well-controlled correlation studies using the same lens are still showing differences in test values particularly at off-axis angles. Although it is true that these differences have been decreased relative to some of the early studies, the situation is still somewhat confused.

The information in the following paragraphs will provide a better understanding of the *status quo*, problems which have been met in developing and using standards, and some of the solutions.

Great Britain

STANDARDS ACTIVITY

Government and commercial agencies have been using photo-electric techniques for over a decade for measuring the line-spread function from which the OTF is obtained by Fourier analysis. The method developed at the Royal Aircraft Establishment (RAE) has resulted in British Standard 4779: (1971); "Recommendations for Measurement of the Optical Transfer Function of Optical Devices." The RAE equipment for measuring OTF is now organized in collaboration with the National Physical Laboratory as the standard of reference for OTF measurements conducted under the control of the British Calibration Service. This Service issued publications 0702 and 0751 which set out the general conditions for testing and approval of a laboratory's equipment and techniques certifying their capability to perform optical transfer function measurements.

These critiques rate laboratory capability in accordance with their ability to meet the values set by the reference laboratory (RAE) for the OTF testing of standard lenses. In addition, there are specified requirements, such as the necessity that the test equipment be mechanically accurate and repeatable, the environment be controlled, the spectral characteristics of the source and sensor be known, and linearity be proved or calibrated.

The RAE is now writing specifications for new aircraft lenses which greatly reduce testing time. The MTF evaluation is for a single, carefully selected spatial frequency. The relationship between this and other *reduced* MTF criteria and the corresponding differences in picture quality under typical flight conditions are currently being studied. They assume at present, that a 20 percent fall in MTF at this single frequency is barely perceptible as a change in picture quality and can be used as the tolerance for acceptability in production specifications. An experimental study is in progress to verify this assumption. The evaluation includes use of photographic emulsion threshold modulation curves.

In many tests the computed value of the MTF using monochromatic light has been the criterion of accuracy. A new polychromatic OTF computer program is now being studied for use in setting the absolute MTF level to which the acceptance figures in a production specification will be related.

INVESTIGATION OF EQUIPMENT AND METHODS

SIRA Institute Image Assessment Group is a U.K. collaborative activity which has headed many qualitative investigations on OTF. Their findings, frequently written in conjunction with RAE are published in papers which are excellent references for those establishing or controlling an OTF test laboratory. These papers include:

- Accuracy in Image Evaluation: Setting up an OTF Standards Laboratory.
- Influence of Optical Bench Errors on Accuracy of OTF Measurements.
- The Use of Simple Optical Systems for verifying the Accuracy of OTF Equipment.
- The Use of Standard Test Lenses for Verifying the Accuracy of OTF Equipment.
- Specifications for Checking the Performance of MTF Equipment at Large Field Angles using a Gimbal Mounted *f*/4, 200-mm doublet lens.
- Dimensions, Tolerances, and OTF Characteristics of the SIRA Group 200-mm Doublet Test Lens.
- Significance of OTF Methods in Assessing Lenses to be Used with Partially Coherent Illumination.
- A Workshop Instrument for Testing Binocular and Other Sights Using the MTF Criterion.
- OTF Standards for Aerial Mapping Lenses.

RESEARCH & CURRENT STATUS

An extensive program of work on the accuracy and reproducibility of OTF measurements made in eight different European laboratories has just been completed and an analysis is in draft. A paper was presented on the results of this analysis at the Symposium in Stockholm, August 27-29, 1974.

Standards in the U.S.A.

ANSI PH2.36

Proposed American National Standard Terms, Symbols, and Notations for Optical Transmission and Reflection Measurements (Optical Density).

Many different optical systems are used in photographic practice, and the number of different spectral and geometric conditions involved are increasing. It has, therefore, become important to expand the scope and versatility of standards that pertain to the measurement of optical transmission and reflection characteristics of photographic materials.

This standard identifies three modes of propagation (one of which is the general mode propagation), three kinds of reference flux, and two mathematical forms, a total of 18 different measurements of modulation. The system of specification provides a standard way of specifying geometric conditions which are closer to practice, as well as the extreme situations, permitting their precise description. It standardizes on measurements such as diffuse transmission density, specular density, the range between the two, projection density, 45° and 0° reflection density, and transmission micro-density, the latter affecting the response of microdensitometers and photometers in OTF and MTF analyses.

ANSI PH2.39

Proposed American National Standard Method for Determining the Photographic Modulation Transfer Function of Transparent Photographic Films (Monochrome – Continuous Tone for Still Photograph).

This standard was reported by the MTF Working Group 1968-72. As the result of circulation for voting further modifications are to be made. The basic standard is already being used by film manufacturers and customers, particularly government, in reporting photographic MTF values and in verifying them.

The Forward, which is not a part of the proposed standard, draws attention to the fact that "One of the advantages of the modulation transfer system . . . is cascading . . . although such cascading would be useful and desirable in systems which include photographic components, this standard does not claim that the Standard Photographic Modulation Transfer Function will necessarily give a representative system response if it is cascaded with other components of the system. Factors beyond the scope of this standard have to be included when precise predictions of the density of fine details in photographic reproduction are to be derived by cascading . . ."[8]

The user of this standard is further reminded that photographic MTF is a measure of the apparent scattering of light within an *unprocessed* emulsion and not a measure of transmittance of the processed image. The gradient of the density-log exposure curve provides a very approximate factor relating the modulation associated with the light scattered within the unprocessed emulsion. Nelson's paper[8] gives a more exact relationship. Frequencies beyond two hundred cycles/mm are not considered.

PH 3.57 TASK FORCE

The American National Standards Institute (ANSI) PH 3.57 Task Force is developing an Optical Transfer Function Standard in three parts. Part I, *Theoretical Background, Definitions, and Concepts*, is in draft from for a final review. Two other sections on Test Procedures and Instrumentation are being written. The approach is to look at the standard as a living, updatable standard initially covering a body of knowledge with present methods and practice, and allowing for issue of addends (without obsolescence of the major body of work) to cover specific situations, such as interface to CRT, eye, etc., and to recommended practices with regard to coherence effects, mechanical and trigonometric precision, documented test lenses for setup and control, trouble zones in setup and measurement, computer needs in analysis, etc. Present plans follows.

Part II, Methods, will contain sine-wave response, square wave, point spread, line spread, pupil function, interferometric methods. Part III will cover establishing master references, (lenses) mounting with full details, dimensions, angles. There will be an appendix of important factors, tables, needs to know, etc. Each part will comprise a complete issue, standing on its own.

If plans materialize this standard will probably be the most comprehensive of any written to date. It may, therefore, take considerable time to reach agreement and publication.

INTERLABORATORY COMPARISONS OF MEASUREMENTS AND COMPUTATIONS

Two extensive studies of interlaboratory comparisons of MTF measurements and computations were made under contract to the United States Air Force. The first well known results reported by Brock and Attaya[9] showed significant lack of agreement on measurements of a 24-inch aerial camera lens, the cause of which was not resolved. A more exhaustive study by Hopkins and Dutton[10] followed several years later, the specific purpose of which was to provide the Air Force with a realistic test of the practicality of making wider use of MTF concepts in the evaluation and specification of lenses.

Eight laboratories participated in computing the MTF of a 24-inch, *f*/6, five-element lens at 0°, 10.4°, and 14.7° field angles. The University of Rochester program was used as the standard.

Results are shown in five tables with frequency values to 100 lines/mm separated into radial and tangential scans. The maximum deviation on axis was 0.03 and +0.02 MTF units. At 10.4° for a radial scan −0.02 and +0.04, maximum values of deviation occurred at 10 lines/mm. (For the standard radial values the table shows the MTF dropping from 0.74 at 10 lines/mm to 0.00 at 40 lines/mm and then rising again. At 100 lines/mm the MTF is 0.10.) Variations of ± 0.02 MTF units are normal for this scan and angle at low MTF values. Tangential scan results for the same angle are much better. At 14.7° (the corner of a 9 × 9-inch format) both radial and tangential scan computed values showed maximum deviations from the selected standard of −0.03 to +0.04 and −0.01 to +0.06.

The authors note that, "Although the computation of MTF or OTF from lens design parameters is, in principle, a simple and straightforward matter, many approximations and simplifications are required in practice to make the actual numerical calculations manageable. Different lens designers adapt different kinds of compromises in their programs for evaluating OTF, and in general get different answers." The spread of MTF values, therefore, was attributed to the ways in which different programs compute the shape of the vignetting aperture, possibly to some variation due to evaluation of the pupil function methods of taking into account the foreshortening of the aperture, and to small variations in the incidence angle of the chief ray.

A comparison was also made between two computing programs for a 10- element, 3-inch *f*/4.5 wide-angle lens on axis and at 30° off-axis. There was good agreement on axis but at 30° they differed as much at 0.2 MTF.

The same 3-inch lens was tested by seven different facilities. Again "the axial values were not too extreme but beyond a frequency of 40 lines/mm the spread was 0.1 or greater. At 30° field, spreads of 0.4 (and higher) occurred between 20 and 40 lines/mm."

Not all of the important features of this extensive report can be contained here and those concerned with standards and monitoring of an OTF testing laboratory would do well to review the many tables and graphs. This author (Norton) believes that only extensive through-focus tests at specified angles and azimuths (costly for both computing and measuring) could have provided more information, isolating (a little further) the metrological problems which appear to have contributed to much of the scatter.

STANDARDS IN THE NETHERLANDS.

Standard for the Measurement of the Optical Transfer Function or the Modulation Transfer Function of Linear Optical and Electro-Optical Imaging Devices (1974). (Philips Co. Standard). Van Leuwen (the author) references the British Standard BS 4779 (1971) for the measurement of space-invariant-lens and mirror-optical systems, noting that "due to the restriction of this standard (BS 4779) to space-invariant devices, which are not afflicted with a considerable amount of veiling glare, the scope of this standard is too small to cover the lion's share of the industrially interesting optical and electro-optical devices. There is still a need for a generally valid standard with a solid physical and mathematical basis, so that space-variant, and devices afflicted with a considerable amount of veiling glare, can also be covered."

In the instance of space-variant devices, the same OTF equipment used for space-invariant devices, may give three different results if line-spread functions, edge responses, or sine-wave response supply OTF data. The most important deviations occur at the low spatial frequency part of the OTF; however, it is not generally justified to neglect the low frequency because of a bounded output field or a considerable amount of veiling glare which may appear as a sudden change of OTF at these low frequencies. In electro-optical devices, Van Leuwen notes the output field is always bounded and the veiling glare can cause a decrease in MTF values by more than ten percent.

The OTF is therefore defined starting with the image *cf* of a point source (actually a slit with length and width selected to provide adequate energy, spatial frequency range, and to satisfy demands of the space-variance od the device under test) introducing the concept of *local* line spread function (LLSF). The Fourier transform of the LLSF is obtained, starting from the OTF, by taking the spatial frequency equal to zero in a direction corresponding to the orientation of the line source. The resulting one-parameter function will also be called OTF. In the event of anisotropy, the one-dimensional OTF depends on the orientation of the light source. Specifying the Fourier transform of the LLSF as a function of the orientation of the corresponding line source is equivalent to specifying the complete (two-dimensional) OTF.

"If the imaging device is linear, the corrected result of a correctly executed analysis of the spatial frequency content of the spatial distribution of the radiance or radiant emission in the image of a static, incoherently radiating, short, narrow slit, given as a function of the orientation of the slit, it will be close to the exact value of the (two-dimensional) OTF of the device under test under the circumstances prevailing during the measurement." Thus the dependence of the OTF on the prevailing circumstances is different for different kinds of imaging devices.

In order to obtain useful measuring results, the relevant measuring conditions during the measurement must be chosen as close as possible to those during normal operation. In this document, sets of measuring conditions have therefore been standardized for a group of devices or their special applications. This standard particularly treats certain devices specifying the sets of measuring conditions and accuracies required. (It seems probable that more types will be added to the standard tests being tailored for production quality control.) The tests presently standardized are for:

- ★ Image intensifiers for passive image-intensifying systems.
- ★ Eyepieces for image-intensifying system.
- ★ Front optics for passive image-intensifying systems.
- ★ Passive image-intensifying systems.

For each of these devices the standard describes the device, conditions which apply during normal operation and the dependence of the OTF on these conditions, the relevant measuring conditions and corresponding tolerances, and recommendations for methods and techniques for measurement.

The Philips Co. standard extends the use of OTF and MTF which they consider the most informative of test criteria for electro-optical equipment, but the bounds and the test equipments are well defined such that results of tests give realistic values.

STANDARD OF OTF IN JAPAN.

A working group of the Japan Optical Engineering Research Association (JOERA) was organized early in 1974 having as a goal the production of an OTF standard by 1976. The standard will cover: (1) optical systems to be tested, (2) definition of OTF and MTF, (3) standard graphical representation of OTF and MTF, and (4) inspection standard for the accuracy of MTF measuring instruments.

The optical system will be limited to photographic objectives with TV, motion picture, aerial, and copy lenses being considered in the same class. Definitions of MTF and OTF will be similar to those in British standard BCS 0751 and the West German standard DIN 58185. A method of graphic representation of data will be selected from five recommended forms.

The use of iso-MTF curves of certain frequencies have also been recommended, but because of the large amount of data involved for through-focus tests, such curves are seldom used. Japan manufactures a large number of amateur cameras in which color film is used and a standard will probably be developed for color.

The working group has investigated methods of inspection for the accuracy of MTF measuring instruments. They considered a standard grating but this is useable only for test equipment based on scanning methods and a diffraction limited lens which has a large *f*/number with a small angular field. The overall characteristics of the equipment are therefore not tested with such a lens. They are therefore proposing to use lenses with known lens data as is being done by the British Calibration Service, and the paper gives graphs of three such lenses with measured MTFs using the *e*-line compared with three methods of calculation. All the axial curves and the one curve at 20° show good agreement.

JAPAN — RECENT TRENDS IN OTF MEASUREMENT

A group of scientists and researchers from Universities and Optical companies began studies of OTF measurements as far back as 1954. The last decade has seen the development of many Japanese instruments for measuring OTF, most being based on the analog Fourier transform method.

The Committee of OTF and the Committee of Lens-Measuring Instruments of JOERA conducted comparison OTF tests on ten typical, domestic (Japanese) equipments, among which five were of the same design. A 50-mm, *f*/2.8 len was used at 0° and 15° angles, radial and tangential. The light sources were monochromatic (*e*-line) and white light. Emphasis was placed on spatial frequencies up to 40 lines/mm.

If the setting errors of the reference image planes were removed, the five C-4 type equipment of the same design, tested with the monochromatic light agreed within approximately 5 percent of the calculated MTF.

The two units of different design if tested with the *e*-line light source showed larger differences between the calculated and measured MTF which appeared to be about 10 percent. If illuminated with white light the results were similar. Mechanical problems remain to be investigated so that the focusing position will agree. A digital Fourier transform method using a knife-edge was studied. It was found that the pitch error of the microscrew that moves a knife edge could be very significant and must be avoided.

The JOERA instrument detects the lateral shift of the knife-edge by a moire scale detector in intervals of one micron. The Canon, Inc. instrument is pushed or pulled, step by step at intervals of 0.25 μm by an electromagnetic vibrator.

"The influence of Noise on the Measurement of OTF by the Digital Fourier Transform Method", a paper presented by Ose, T., and Takeda, M., Institute of Industrial Science, University of Tokyo, Japan, was presented at the SPIE-OSA meeting in the U.S.A. in May 1974. This theoretical study concludes that: (a) for stationary noise the multi-slit method is effective in reducing error of the OTF; (b) the knife-edge method can also be used effectively provided the sampling interval is selected closer than one-third of that required by the sampling theory; (c) for shot noise, the multi-slit gives a slightly larger error than that of the single slit, but much smaller than that of the knife edge method; (d) the experimental comparison of the multi-slit and knife-edge show that the multi-slit methods has an advantage if used to measure the OTF of dark-line images. The study finds that in applying this method it is necessary that the step of the scan precisely equal the width of the elementary slit. This method can be used for measurement of OTF of lenses used in infrared imagery where the dominant source of noise is detector noise, which is independent of the signal intensity and consequently stationary.

In 1973, Mr. T. Asaeda, et al. (Canon, Inc.) produced an instrument in which a slit is used as a scanning aperture. In this instrument, a mini-computer works not only for a digital Fourier transform of the measured line-spread function but for data processings. The influence of noise is reduced by repeating the measurement of intensity at each sample point and the fluctuation of dark current is avoided by the subtraction of a constant current from each sampled output current. The constant current is the averaged one at several sampled points on the foot of line-spread function. The lens assessment in the recent lens design technique, needs MTFs in high-spatial frequency domains. The digital Fourier transform method will be applied more and more in MTF measurement.

A new instrument designed to measure and display the OTF and based on analog Fourier transform method has been produced by Nippon Kogaku Kogyo K.K. according to the specifications of the Japan Camera and Optical Instruments Inspection and Testing Institute (JCII) in 1973. A rotating Siemens' star-type square-wave chart is used as an object target in this instrument. Special attention is given to the precise production of optical bench and mechanical parts, and sophisticated electronic circuitry process the signals fed into the *X-Y* recorder. Now, this instrument is regarded as a standard instrument of OTF measurement in Japan, both MTF and OTF being obtained with accuracies.

Two working groups of JOERA are conducting studies on methods of checking the accuracies of measured and calculated OTF. Three kinds of standard lenses are being designed and fabricated for tests of on-axis measurement, off-axis measurement, and condition of illumination. All of the OTF measuring instruments will be tested again using these standard lenses in 1974.

REVIEW.

A review of the standards, supplementary controls, and testing activity associated with the standards shows a number of important facts that must be considered by the ISP Commission I Working Group on Optical and Modulation Transfer Functions. These are:

- There is increasing use of OTF and MTF in evaluating optical and electro-optical devices.
- Correlation testing results show good correlation on axis (current tests) and important differences off-axis. Many differences appear to be due to meauring equipment (or bench accuracy) and the sensitive focus.
- Through-focus tests at many off-axis angles and two or more azimuths (similar to present resolution tests) are time consuming and expensive. For manufacturing or acceptance testing, much shorter tests are needed which are still adequately selective.
- Testing methods and equipment will have to vary in accordance with the device being tested. Standards should be provided for all optical and electro-optical devices.

- For the manufacturer who has a specification in terms of OTF or MTF on an operational system, methods of testing elements and subassemblies that go into that system (and which may have been purchased and therefore require acceptance on a separate test prior to use in the system) will have to be found so that quality tests can separate out the unacceptable, such that they do not degrade the system. This is where cascading is useful.
- In all instances only a scientist or engineer familiar with the requirements of precision equipment (mechanically, electronically, optically, thermally, the problems of partial coherence, noise, phase, etc.) armed with proved computer programs can specify the test and test equipment.
- If the results of the theoretical design are to be used as the criteria of accuracy, designers should agree on the approximations which simplify the computing; or contrariwise, the most rigorous program should be used so that the most exact results are computed. In the first instance, tolerances should be estimated to form a basis for physical tolerances.
- Camera systems generally use sources of illumination with long spectral ranges. For aerial cameras the range varies with the film of the sensor. It seems necessary that the lens be tested using the same spectral range and amplitude if the tests are to produce values which are useable for the system. Results using monochromatic sources can perhaps be more easily compared with design data as a means of control, but the color aberrations affect both lateral spread and focus and it would be difficult, if not somewhat indeterminate, to cascade MTFs to wide band system performance using monochromatic data.

ISP STANDARDS PROPOSAL

Based on the above (which is doubtfully all inclusive) the Working Group has elected to expand Section 6 of the Calibration of Photogrammetric Cameras to include, if possible, all of the techniques presently known. It is not expected, however, that this can be truly comprehensive.

Optical, Modulation, Phase Transfer Studies, Figures of Merit, Microdensitometry, Noise.

A number of studies show that caution must be observed in cascading of functions and in obtaining accurate MTF and OTF values. Suppression or smoothing of noise, partial coherence effects, phase, as well as the test equipment must be evaluated for the application of the system being tested if values other than locally relative must be known.

DEVELOPMENT ADJACENCY EFFECTS (U.S.A.)

A study [12] at the Kodak Research Laboratories shows that only in the absence of adjacency effects does the MTF of the film represent the effect of light scatter that occurs within the emulsion during the exposure. The authors call this unique curve the *optical MTF* noting that it depends only slightly on the exposure level and the modulation of the target input. Adjacency effects must be considered in an *effective* MTF because results now depend on exposure level and input modulation.

A formula has been developed relating *optical* MTF and a family of *effective* MT curves. The mass of silver produced by the average exposure of the sine-wave target must be used in conjunction with the chemical spread functions. The chemical spread function derived in this article predicts the behavior as a function of exposure and modulation.

The theoretical derivations were tested experimentally using Kodak Panatomic-X film, the series of film-development combinations exhibiting chemical adjacency effects being measured for MTFs. In these experiments the MTF significantly increased as the mean density of the sine-wave exposures. For a given density the lower modulation target gives a greater MTF.

A further complication exists if one wishes to predict which of two negatives, whose MTF curves are known, will produce the better print because the harmonic distortion of the input signal due to nonlinearity in the transmittance versus the exposure curve of the film may cause significant loss of information. This is because the higher harmonics created in a negative cannot be resolved in the printing stage unless the optical MTF of the printing system and the optical characteristics of the print material are perfect. Thus, what may be gained in micro-contrast due to edge effects, may be lost if the gamma of the negative is so high that harmonic distortion becomes excessive.

FIGURE OF MERIT AND MERIT CURVE (FRANCE)

In the paper[12a] presented by Pauleau at the 1972 Congress, he suggested a generalized method of evaluating the MTF for a number of field angles. He bases the method on the Area-Weighted-Average Resolution (AWAR) used in the U.S. substituting a fixed modulation M for R. The formula then became:

$$\mathrm{AWAM} = \left[\sum_{i=1}^{\mu} \frac{A_i}{A} M_{Ri} M_{Ti} \right]^{1/2}$$

where A is the area of the format, Ai is the sub-area usually the annulus ring, M_{R_i} is the modulation on the radial line at an angle centered in the sub-area, and M_{T_i} is the modulation on the tangential line at an angle centered in the sub-area. A single curve is obtained by using selected frequencies.

MICRODENSITOMETRY (U.S.A.).

The problems of microdensitometry as caused by partial coherence and flare light have been considered by Swing and Grimes.[13] Grimes[14] proposes a *Linear Microdensitometer* where the sample is illuminated by a slit focused on a sample by a high-quality condenser, baffles between the condenser and the slit acting to control stray light. Approximately all of the light transmitted through the sample is collected by an optical element. The system has a number of advantages:

- ▲ The output is independent of the partial coherence of the source;
- ▲ There are fewer focusing and alignment problems;
- ▲ Because there is no sampling slit, the overall system transfer function is improved;
- ▲ The measurement of singly diffuse density makes interlaboratory comparison easier.

THE SIGNIFICANCE OF THE PHASE TRANSFER FUNCTION (U.S.)

The phase of the image transform is far more important than the modulus according to Shack[15] because an image in which the modulus is drastically altered is still recognizable, whereas corresponding phase changes completely destroy recognizability. Many instruments measure only the modulus, it being a matter of great practical convenience if phase can be neglected. Shack shows that under general circumstances the phase must be considered and, if significant, some method found of incorporating it into a specification of image quality.

It is principally in the area of image evaluation that the question of the significance of the phase-transfer function must be faced. Both the spread function and the transfer function are determined by the complex, fundamental pupil function. The modulus of the pupil function is determined by the geometry and transmission of the pupil, whereas the phase is determined by the aberrations.

The phase-transfer function is shown as depending on the location of the origin in the description of the spread function. If the spread function is asymmetric and the peak of the asymmetric blur is used as the origin (as would be natural in measuring photogrammetric images), very little harm would be done in evaluating the MTF, but the asymmetry itself would introduce an error in location of the object.

One must be careful in dealing with the modulus alone, however, even though the spread function may be symmetrical. This is true if the nature of the spread function is such that its Fourier transform, although purely real, has strong negative components. There are situations in which the inverse transform of the modulus does not correspond well to the true spread function showing the modulus to be overly optimistic. Shack concludes that for noncoherent image-forming systems, the quality of the image in terms of the spread of the spread function is adequately judged by the modulus of the transfer function as long as the phase-transfer function referred to the peak (not the centroid) of the spread function, is well within a quarter cycle over the range of significant values of the modulus.

NOISE IN MTF MEASUREMENTS (U.S.)

Slaymaker[16] notes that in MTF measurements are three sources of noise which can enter at almost any step which must be considered: those introduced experimentally, those due to the quantum nature of light itself, and shot noise from the photocathode of the photodetector. Assuming that the first two can be reduced to negligible values, he deals with shot noise which appears as a periodic term added to the true value of the OTF. He shows that in making an OTF measurement by means of a knife-edge scanner, the effect of the shot noise can be reduced to an acceptable level by establishing a maximum value for the scan velocity. The seriousness of the noise can then be calculated as a normalization error and an upper bound on the variance of the MTF from known values for the electrical bandwidth, the time to make the scan, the gain of the photodetector and the anode current. To verify the noise calculations experimentally, Slaymaker measures the variance in the MTF data. He then calculates the mean and standard deviation for the data at specific spatial frequencies for a number of repeated scans.

A comparison of the calculated and experimental results obtained with a 0.1 × Micro Tropar lens having a focal length of 26 mm, an f/number of f/1.6 and a theoretical cutoff frequency somewhat above 1200 cycles/mm, shows good agreement at spatial frequencies approaching the theoretical cutoff. At zero frequency, however, the measured value for the standard deviation of the data is more than twice that of the calculated normalization error. He explains this by pointing to the possibility of other sources of experimental uncertainty in addition to shot noise.

His basic premise that the noise can be held to an acceptable level is upheld, however, and for the specific lens and test parameters used is 0.0035 MTF units at zero spatial frequency and approximately 0.018 MTF units at 1200 cycles/mm.

Interferometric Methods (U.S.)

Interferometric testing essentially measures the pupil function from which the optical transfer function, the spread function, and aberration coefficients may be computed. The pupil function must be used to evaluate cascaded optical systems and systems employing coherent or partially coherent illumination.

Most quantitative interferometric testing systems are expensive, time-consuming, and require operational expertise. The application of the Wavefront Shearing Interferometer (WSI) developed at the U.S. Bureau of Standards[17] (NBS) eliminates some of these undesirable features, employing an interferometric cube into which the adjustments are fixed. The WSI into which the cube is installed is portable and easily set up on an optical bench.

The resulting interferograms, however, cannot be interpreted by simple inspection in terms of wavefront aberrations. Hence the major cost of testing goes into data reduction and analysis.

The lens under test is set on the bench for either finite or infinite focus. Beyond the focus, in diverging light, the cube is positioned. An auxiliary lens photographs the fringes on film.

The cube interferometer operates by amplitude dividing the incoming wavefront into two equal parts and introducing a small angular shear into one of the beams. For two 45°-90°-45° prisms contacted along the diagonals to form a cube, the pivot point of rotation lies in the plane of the back face of the cube. A small shear is then introduced.

As the cube is not used in parallel light, corrections are made for the known aberrations which are introduced by the optical path differences.

Working with photographic transparencies of the interferograms the test data is supplied in fringe-peak locations. The technique of autoconvolving the fringe density profile in the vicinity of a maximum or minimum was used to locate the fringe-peaks. (The peak of the autoconvolution function corresponds to the fringe-peak.) This method has the advantage of averaging grain-noise effects during integration and, according to the authors, appears to be as accurate as the scanning interval allows. It is necessary to orient the interferograms orthogonally so the resulting data from the scanner is registered in a common coordinate system.

The auxiliary lens that photographs the fringes is located such that its aberrations do not affect the measurement of the fringe locations.

Comparison tests were made using a 50-mm SIRA standard lens. Within a spatial frequency of 100 lines/mm there was good agreement on MTF values with those certified by the British Calibration Service.

The WSI system has been demonstrated at NBS to be a versatile, inexpensive, and simple alternative for interferometric testing of lenses. The authors note that further improvements are possible, particularly to the computing techniques and (this author, Norton) would like to see correlation testing at significant field angles.

PTF/MTF Applications.

U.S. Air Force Image Evaluation Program[18]

Some of the biggest disadvantages of the use of MTF have been the cost and sensitivity of test equipment and the test and analysis time. These problems were faced by the Air Force Avionics Laboratory at Wright-Patterson Air Force Base by installing high-speed, automated equipment under close quality control, and testing many quantities and types of camera systems.

The Dynamics Environmental Evaluation Branch notes in the paper on "Quality Control as applied to Imagery Analysis" that image-quality aspects are becoming increasingly important to the Air Force. More cartographic and reconnaissance systems are therefore, being analyzed through an evaluation of their recorded photographic performance, some negatives being exposed under unknown environmental conditions and others in laboratory studies under controlled environments. Simulated condition, equivalent to the extremes encountered in actual missions are also analyzed with the Mann-Data Micro analyzer to determine image quality.

Selected image edges, traced with the microdensitometer, are recorded on high-speed magnetic tape. This recorded data is then operated on by a CDC 6600 digital computer to provide edge-trace data, in either tabular or graphic form, for detailed visual inspection. Various computer programs are then available. It is routine to obtain information on:

- Exposure
- Target detail and contrast
- Granularity
- Density range with maximum and minimum exposure, and log exposure data for obtaining absolute density exposure values.
- MTF when operated on by the Fourier transforms
- There is, of course, much additional specialized information available through the analysis of the micro-densitometer data. This may be selected as desired.

These routine MTF tests and supplementary analyses have supported the quality functions by proving that quality systems have been procured and/or photographic performance is stable. The equipment and test techniques being at "the state-of-the-art" are also used for research studies. The speed of processing, that is available through automation and use of computers, greatly reduce test and analysis time, resulting in lower cost-time per unit test. The nearly *real-time* for answers to the question of quality of images makes it possible to make confident equipment decisions for an important mission, or design development, or to investigate performance problems.

Imagery obtained by the Canadian Air Force with the Wild and Zeiss reseau cartographic cameras being used in the study conducted by the Commission I Working Group on Image Geometry, will be analyzed by this facility. Results will be reported at the 1976 ISP Congress.

IMAGE CONTROL AND EVALUATION (U.S.)

In a concerted effort to optimize the information content of aerial photography, the Air Force has instituted a service-wide program called Sentinal Sigma. The program is designed to control quality by standardizing procedures, first black-and-white photography, and later other types, such as color, nonconventional, etc. The standardization and guidance will set the basic documentation and direction for USAF Commands more effectively to manage, utilize, and evaluate their photographic production resources and to unify procedures and techniques.

An integral part of the effort is the Imagery Evaluation Working Group. This group is directed: (1) toward the establishment of tying together objective and subjective measures for determining image quality, and (2) toward establishing a common technical photographic language between engineers, operation personnel, users, and project managers. Techniques such as Modulation Transfer Functions, visual edge matching, and holographic models are being used to determine clearly the quality and operational performance of Air Force reconnaissance platforms. These and similar techniques are being compared to established operational methods of evaluation.

MTF ANALYSIS APPLIED TO SATELLITE IMAGERY (U.S.)

Welch[19] has written a number of papers for the U.S. Geological Survey reporting on techniques and results of analysis of satellite imagery using resolution and MTF criteria. (Welch will present a paper at the Stockholm symposium on such analysis, so only mention is made here.) (Attaya and Corbett at Itek have also used MTF analysis techniques on Skylab photography.)

INDUSTRIAL USES OF MTF

ITEK CORPORATION

Itek employs various image analysis techniques[20] in both design and testing of optics some of which are considered unique. An MTF computing scheme permits the prediction of image quality for the most general cases of field angle, image orientation, spectral region and film characteristics. A design can be adjusted to the optimum with this program allowing, for example, filter characteristics to be balanced against aberrations and exposure time for maximizing resolution. The MTF techniques are also used for evaluating fabrication tolerances and for predicting the effects of thermal variations on system performance. Computer support is provided during optical fabrication through melt-data adjustment, image-quality analysis, and interferometric test data-reduction to provide surface error contours and rigorous-system image-quality analyses. Manufacturing processing corrections results.

The lens designed at Itek for the S-190A multiband camera of NASA's Skylab[21] program was evaluated in the design stage, the manufacturing stage, and the performance stage using MTF techniques. MTF techniques (with additional analyses) of the Apollo 15 panoramic space photography showed that this unusual camera was functioning close to its predicted quality during its complete mission.

Another MTF evaluation is used on fiber optics.[20] A fiber optics faceplate is composed of an ordered array of small individual light pipes which transfer images from input to ouput. Conventional methods of investigating the fiber-optics image-transfer process utilize the spread function and the edge response as a basis for transfer-function calculation. Unfortunately, a transfer function calculated from a fiber-optics spread function does not have clear meaning. A holographic method is, therefore, employed, photographic recordings being made of the summation of sinusoidal fringes at the input surface and at the output surface of the fiber optics. From these the Fraunhofer diffraction patterns are produced. Because the irradiances of the narrow sinc light distributions in the Fraunhofer diffraction patterns are directly related to the amplitude of the sinusoidal irradiance variations, the pair yields a fiber-optics transfer factor, and a statistical MTF, the latter being a measure of the average performance. Tests were conducted with techniques that provided additional information on lateral and rotational distortion of fibers, missing or broken fibers, and resolution.

FAIRCHILD CAMERA & INSTRUMENT CORP.

At Fairchild Camera, MTF and OTF have found their primary applications in optical design and diagnostics. As an optical design tool evaluation, based on contrast and phase, calculations have proved invaluable in the large-scale computer-oriented design process. Although MTF has not yet entered into the merit function formulation to use in assessment of system quality, it typically outweighs other criteria.

In the evaluation of prototype systems a correlation between paper design and hardware execution is essential to development process. As of this writing (1974) modulation and phase measurements provide the best readily available measurements for the establishment of such correlation.

It has not yet proved possible to utilize MTF and OTF evaluation in routine characterizations of wide-angle lenses such as those typically used for photogrammetric purposes. The difficulties encountered in attempts to do this lie both in physical contortions (the very precise adjustments and locations of equipment parts) necessary and the uncertainties in the results of subsequent analysis of the data obtained.

It is envisioned, however, that routine contrast measurements with electro-optical equipment can be made to augment, or eventually to replace, other forms of testing in the screening, and even perhaps in the final evaluation, of lenses having more modest angular coverage.

STUDY OF EDGES FOR THE LOCATION OF PHOTOGRAMMETRIC IMAGES (U.S.)

A study made at Ohio State University[22] is concerned with the detection and measurement of photographic images, and proposes the edge as being the quantity most intimately related to photographic measuration. The selection of the edge is also considered valuable because of its relation to the spread function whose Fourier transform leads to the MTF. The stated objective of the study was to search for a meaningful specifier of image quality. Image quality is defined in the terms of photogrammetric application to mapping as the measurability of an edge as determined by the degree of agreement between the subjective edge locations from four experienced observers. A secondary objective was to locate where the subjective edge is determined to be located in reference to some measurable quantity.

The study is detailed in the evaluation of edges and image quality examining the published, frequently contradicting statements of experts.

The conclusions of this study (which should be applied to a variety of photographic images for further proof) was that: (1) the observers located the subjective edge slightly into the less-dense region as measured from the inflection point of the intensity edge trace, a normal value being 30 seconds of arc. At the ratio of 10 seconds of arc equal 1 μm at the photograph this is $\pm$ 3 μm. (2) Any quantity related to density correlated with image quality better than its corresponding intensity quantity, acutance being an excellent specifier. A new quantity decutance, had the highest correlation (decutance, $D_e = A/\delta$, where A is amplitude and δ is dispersion, practical units being in terms of density/micrometer. (3) The position of the pointing did not correlate with image quality (as defined above) which suggests an individual personal edge preference by each observer. Observers point more precisely on some edges than others, but a particular edge producing high-pointing precision may vary according to the observer. (4) The higher derivatives (2nd, 3rd, and 4th) of the intensity edge trace revealed no information that was not already discernible from the edge trace or its first derivative. (5) Neither the modulers of the Fourier transform of the intensity spread function nor the cut-off frequency as computed by Cooley's Fast Fourier Transform algorithm displayed any correlation with image quality.

O'Connor[23] had shown in a previous study that the error connected with centering a measuring mark in a target was less than the ± 3 μm error of this study. As such, in any photogrammetric task where it is possible, Thompson[22] suggests that greater accuracy will be achieved if edge measurement can be avoided.

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Articles for Next Month