# ON THE INFORMAL HISTORY OF IMAGE EVALUATION TECHNIQUES AND PRACTICE

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## FOREWORD

We are in the high resolution era in aerial photography. From a WW II estimated performance of 10 -- 12 lines/mm on the negative, we now talk about resolution of 100 lines/mm (and higher).

The advances in camera and lens design and the availability of remarkable new emulsions have emphasized the problems of testing photographic systems.

Nothing is as fragile as high resolution, and to get it, to hold it, and to preserve it is extraordinarily difficult.

The discussion in this paper is designed to furnish some perspective on the development of camera-lens-system testing techniques, and urges restraint before we get committed to new test methods which may produce more arguments than universally agreed-on results. In addition, questions are raised on the fundamental meaning and purpose of tests.

# ON THE INFORMAL HISTORY OF IMAGE EVALUATION TECHNIQUES AND PRACTICE

by

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## INTRODUCTION

The title of this paper follows from the fact that I have spent the last nine years at RAND. It is generally known that we have no laboratories, no aircraft, no collimators, no sensitometers, no microdensitometers, and no testing facilities.

I say this freely because there is little chance that I can get away with the notion that I am now working on image evaluation. Working on image evaluation requires both images and hardware.

Despite the fact that for the last nine years I have been at RAND, for the preceding fourteen years I had a "temporary" job in the old Aerial Reconnaissance Laboratory. We had lots of fun and excitement there. We participated in and watched the development of aerial reconnaissance as applied to WW II. We also were in on the beginning of aerial camera testing, laboratory testing, and had the opportunity of seeing the things we tested actually used to produce results. My remarks will deal principally but not entirely with that phase of my

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activities.

II. WHAT IS THE PROBLEM ?

What is the problem of image evaluation, and how did it arise? This problem, like other problems, arose because there was more than one person involved in aerial reconnaissance: there was more than one company, more than one group of workers, more than one laboratory. The need for standardization, the need for buying, procuring, testing, and having these things done interchangeably and repeatedly, has produced much argument over the years. Let's clarify our subject first.

All special, obscure, and lesser cases do no more than slightly blur the fundamental point that we are primarily concerned with the kinds of images produced by high-quality aerial and similar cameras. In particular, we are interested in rendition of fine detail produced by such cameras. We are not talking about photographs produced to esthetic standards. Portraits, landscapes, travel photographs, and the like are interesting, but of no concern.

The last remark is not meant to deny the obvious fact that many aerial photographs are beautiful, in and of themselves. Many aerial photos are suitable for framing, hanging and viewing, as a piece of esthetic intelligence. The production of an esthetically complete and beautiful photograph, as in some kinds of low-altitude oblique photography done for commercial purposes, is cited as an example of what is of little relevance to today's discussion. Why? Because we are almost always interested in fine detail.

I emphasize this point. The fundamental difference between the aerial photographs concerned with fine detail and others is that

landscapes, portraits, are viewed in toto for effect, for understanding, for appreciation. Talk and consideration of composition, shapes, tonal balance, dominate. One seldom looks at the aerial photographs we are talking about in toto; they are usually examined with a microscope or magnifier. We back off from landscapes to look at them; we converge on high quality aerial photography in order to look at details of interest.

Again, I want to repeat this is not meant to imply that we are concerned with the trees and not the forest. Very often, for certain kinds of problems involving the use of aerial photographs, it is important to back off as far as possible and see the form and structure and relationships of what we subsequently look at in detail. This is certainly true for the various kinds of urban area analysis where patterns predominate. It is sometimes important for orientation purposes to look at mosaics, at huge views. Presentations are often made in series: the overall view comes first, then a series of enlarged sections follows. And it is certainly true for certain kinds of geological photography where it is the vast expanse that produces the feeling instead of the microscopic examination. But the point I made, that the difference between the two kinds of photography depends on the viewpoint, whether one examines the photo in extenso or in detail, remains.

The old Aerial Reconnaissance Laboratory pioneered in testing, pushing standardization of test methods, forcing agreement between industry and government, standardizing targets, and doing many othe. things. There was a good reason for our being in a position to do this.

We at Wright Field were at the crossroads of research and development,

procurement, use, and even more important, had a considerable voice in the expenditures of a good bit of money. Contracts and procurement were involved. This gave the Reconnaissance Laboratory a fundamental and decisive advantage over many other able groups who were proposing other forms of targets and test methods. As is well known by now, the three-line resolution target with an aspect ratio of five to one, came from the Wright Field Aerial Reconnaissance Laboratory. Other charts were competitive with this target at the time. Cobb's charts, the two-line target of England; Howlett's doughnuts from Canada, and others. During World War II, Selwyn had even proposed sine-wave targets. Clearly, he was ahead of his time by many years, but I think it fortunate that we didn't use such targets during WW II, or we'd never have had standardization, procurement and the massive improvements which followed.

I do want to clarify this a little more. Everyone in the testing business thought that <u>his</u> test better simulated the real world, or gave data more useful to the designer, the using service, or to someone.

Everyone in this maelstrom of argument was sincere. But remember that the whole war didn't last very long -- at least compared to the half life of standardization committees!

## III. <u>SOME RELEVANT HISTORY</u>

I think a few historical notes will help show how we got where we are. In 1940, when I arrived at the Reconnaissance Laboratory, our lens testing facility consisted of a big Goerz Dogmar lens used

as a collimator, a square root of 2 high contrast target which was photographed through the lens under test onto glass plates coated with some obscure spectroscopic emulsion, probably a process emulsion of one sort or another. The Dogmar was accurately named. It was a "dog" and the belief that many people had in it at that time was nothing but dogma. The largest aerial photographic lens we had at that time was a 40" f/8, and it was a match for the collimator. It was not an especially good lens. Although it produced acceptable images in the laboratory on a test bench, it produced simply terrible pictures when taken to high altitude (at that time, "high altitude" was 30,000 feet).

Two things happened; in the first instance, I began to wonder what kind of resolution we were actually getting from the air. That the aerial photographs being made were terrible was perfectly obvious; no targets were needed to establish this fact. I made some targets out of huge sheets of photographic blotting paper, white and black. Whenever I would hear that a flight was going up, and whenever I could persuade the pilot to kindly steer himself over my targets, I literally nailed these to the ground on, of course, a temporary basis. I always located these targets near the accelerating runway at Wright Field, which provided a distinctive intersection with the short runway, and an easy check point for the photo-pilot.

We began to get resolution targets on aerial photographs. This was, perhaps, in early 1941. We discovered (or rather, confirmed) what is generally known and accepted, although it came as a big surprise to most of us, -- pictures made from the air do not exhibit

as good resolution as photographs made on the test bench.

The second thing we were led to was the discovery that sea level focusing in our laboratory was not necessarily the proper focus for cameras and lenses taken to high altitude in near-vacuum conditions. We then made what we ourselves regarded as a brilliant and fundamental investigation into the effects of index of refraction variations and temperature changes on focus. This was especially relevant to the use of telephoto lenses, of forty inches or thereabouts in focal length.(1)

There is an interesting (and now amusing) sidelight to this story. We mentioned this "brilliant investigation" one day to Dr. James E. Baker, who was then working in our laboratory busily designing his justly famous forty-inch f/5.0 distortionless telephoto lens. He looked at us with considerable surprise and said, "I thought everyone knew that." All this time he had known about the temperature and pressure effects, had taken account of them in the design of his lens (which came out to have automatic temperature and pressure focusing), and did not think to mention this to anyone because he assumed that we all knew it. Well, you may well believe that this deflated us quite a bit. But we were still ahead of most others!

As I noted earlier, our original targets varied by the square root of 2. We soon found that the least count given by the square root of 2 targets was insufficient, and we went to the cube root of 2 targets which have a line width per cent spacing of about 26 per cent. Subsequently, and as at present standardized,(2) we went to the sixth root of 2 targets, with a target spacing of about 12 per cent. We standardized early on a five-to-one ratio of line-length to line-width

(for the single line) in an effort to get away from the long-line phenomenon (to be discussed later). Somehow, we were trying to simulate ground objects; somehow we felt the targets were better than point sources. At least, we attempted to simulate what the user himself photographed.

We felt that very long-line targets aren't too useful because of the apparent high resolution obtained. This results from psycho-physical integration of multiple looks along the length of the line. There are numerous and classic illustrations of this. Perhaps the best example I know is that found in the famous picture taken from a Viking rocket in 1948. This photograph is reproduced in Reference 3. Briefly, the railroad from El Paso to Alamogordo shows up loud and clear, as do others, yet the resolution of the photograph is no better than perhaps three to five hundred feet or so. Clearly this figure of several hundred feet has very little relation to the ability to see such long lines.

The reason for picking three lines instead of a large number of lines was this: we occasionally found cases of spurious resolution, wherein more lines would be resolved than were actually present to begin with. Now, if one made a resolution test, and started counting down from those targets which are easily resolved, continuously without skipping, he would soon run out of resolution. But if he continues beyond this limit he may occasionally see what appears to be resolved lines (beyond the previously determined limit). However, careful count may show four lines where there were only three in the original target. The easiest way to simulate this (although it is far from an accurate

representation of what is going on) is to hold your spread fingers a few inches above a sheet of paper in a room which has multiple lights casting shadows. The inter-play of the shadow patterns produced by the overlapping umbra and penumbra effects occasionally seem to produce images of more fingers than exist on the hand.

Briefly, this was the reason for no more than three lines per target. Thus the fundamental objection to targets which have perhaps ten, twenty or more lines per pattern is the impossibility of accurately counting the lines at high resolution and making sure the resolution is not spurious. Also, and not entirely of secondary importance, it is easier to make three-line targets than targets which have many more elements to each pattern.

We improved our collimators; we got bigger ones; we went from refractor to reflector collimators. We improved the targets, improved the emulsions used in testing lenses, and made numerous other mechanical improvements. Everything increased the precision of the work. Needless to say, our lenses seemed to improve during this period.

I say this with obvious tongue in cheek; our improved test methods gave better results. We never stood still long enough to go back and take an old lens which was tested by the methods available in 1940 and earlier, and check it out on more up-to-date systems. We could have calibrated and estimated the improvement due to improved test methods. For example, one day we decided to do something about the vibration we were having on the test bench (generated by air conditioning machinery, etc.), and slipped an Edgerton flash lamp into the collimator, cutting down the exposure time. The resolution improved. While this

is all very good for improving test methods and improving resolution and getting better results, we seem to have lost a lot of history. The old card files are literally valueless, but this is a small price to pay for progress.

An interesting thing was happening to some of us at that time. Being brash, young, eager, energetic, and very scientific, we looked down our noses at anyone who didn't use numbers and used words other than "resolution". I remember this well, to my present dismay and embarrassment. I remember the bad time that I gave several old-time photographers who, being fairly sharp observers, but completely "unscientific", kept telling me that they could see differences in photographs made with various commercial lenses. I recall their saying that they could see the difference in pictures made with a Dagor lens and a Tessar lens. They used words like this: "The Dagor gives wiry sharp pictures." "The Tessar gives crisp pictures."

Being a hot rod on the collimator, I kept saying: "Look, don't give me that kind of jazz. What's the resolution? That's the only thing that counts." What they were talking about, we now realize, was the character of the resolution before we ran out of it. This is, of course, what is fundamentally wrong with the measure of resolution as used alone. System resolution is an end point measurement of an entire characteristic curve with the measurement being taken at the point where you run out of the quantity being measured. Thus resolution as we measure it is a threshold value only.

Let's now change gears and look at some early attempts to see how system resolution limits are determined by the interaction by

various components of a system.

I have previously, and on various occasions, related the account of the development of the reciprocal formula.

Restated, if $R_i$ are the resolution limits of the separate components, for example, $R_l$ for the lens, $R_f$ for the film, $R_p$ for the printer, $R_m$ for image motion, etc., and $R_s$ is the combined system resolution, they combine (according to this simple formulation) the following way: $\frac{1}{R_s} = \frac{1}{R_f} + \frac{1}{R_l} + \frac{1}{R_p} + \frac{1}{R_m} + \text{----} = \Sigma \frac{1}{R_i}$. In Reference 4 I describe not scientifically, but vividly, the origins of my work on this subject.

General Goddard asked me for help in getting some newly-commissioned amateur photographers off his back. He asserted that they kept bothering him with claims that they could take a small camera like a Leica, go up to high altitude, take a sharp photograph, and enlarge it to equal the quality produced by a very long focal lens camera, say of twenty-four or forty-inch focal length. The fact that they never did it, and were never able to demonstrate the equality of the small camera and the big camera, did not prevent long arguments and much time being wasted.

I recently found my original notes on the subject, which I had prepared for General Goddard. They contain a derivation of the formula which I have never before published. (I should say, I never dared to publish.) I have always insisted that the formulation was entirely heur' tic. But to put a semblance of scientific stature on it, I derived it.

That derivation is as follows: Consider an infinitely narrow line in real space, being imaged by a real lens with its limitations. The

lens would take this long infinitely thin line, and spread it out (in the aerial image) to a width $W_\ell$; this is the image width due to the lens itself. Similarly, consider an infinitely narrow line produced by a non-existent perfect lens and imaged on film. The film, having a resolution limit all its own, would take this infinitely narrow line and spread it out to a line width $W_f$, the limiting width due to the film. Now consider the image of the infinitely narrow line as produced by the lens being spread out to $W_\ell$ (just before it hits the film); the film, receiving this image, would perform its spreading on each edge, making a total spread of $W_f + W_\ell$. (This is easily recognized as simple addition of spot size diameters.) But this is not very scientific. I simply introduced the convention that $W_f = 1/R_f$ and $W_\ell$ is $1/R_\ell$, converting widths to resolution numbers, thus producing the ancient formula $1/R_{f+\ell} = 1/R_f + 1/R_\ell$.

It would be preposterous to assert that, at the time the formula was produced, we were not aware of the fact that lines are not imaged entirely black and entirely white, that there are edge gradients, and that very few things combine in this simple reciprocal fashion (two conspicuous exceptions are, of course, the formula for object/image distance in optics, and the formula for adding resistors in parallel). In my original notes, I noted the fact that it would be more logical to combine these as the inverse square. Gaussian distributions can be treated statistically; all this, in fact, is their outstanding and major advantage. But to us the advantages of simple exposition and easily used formula clearly outweighed the disadvantages of a (probably) better and harder to use formula. Interestingly enough, Kingslake[5]

discusses these effects and gives an example which exactly fits the reciprocal formula. He told me later that this example was purely fortuitous!

The following example will show how these resolutions combine. Consider a two-inch lens, which gives ninety lines per mm by itself, and a scaled-up version, of 6 inch focal length, which gives 30 lines/mm. Consider both of these lenses used with film which has a limit of 45 lines per mm. By the simple formula given above, the combined resolution of the two-inch lens and the 45 line per mm film would be 30 lines per mm. By the same token the resolution produced by the six-inch lens would be found to be 18 lines per mm. But now the two-inch negative must be enlarged to the scale of the six-inch negative and (allowing no losses due to the enlarger, which in fact would introduce a similar reciprocal term all its own, and further degrade the resolution) the resolution of the enlarged two-inch negative would be 10 lines per mm, considerably less than the 18 lines per mm produced by the six-inch lens. This exposition and this particular example has been widely used; it "explained" why you get better results with long lenses. Be sure to note the conservative assumption utilized here: that the resolution produced by a six-inch lens is one-third that of a two-inch lens. Such is hardly ever the case. While long focus lenses usually yield less resolution than a short lens (with resolution being measured in lines/mm in the focal plane) it is not always less; in any event, it never scales down inversely as focal length.

The difficulty with a formula for resolution obtained by adding

reciprocal squares of resolutions or, as is now fashionable, reciprocal resolutions to the 1.5 or 1.8 power, is that such formulas convey a false sense of scientific truth and precision to the matter under discussion. When using the simple linear reciprocal formula, everybody knows or suspects that it is an approximation. I have never said that it is other than heuristic; a false sense of certainty and precision about such matters is really unwarranted, and this is what is really wrong with more complicated formulations.

Despite these continuously applied caveats, it is interesting to note that Dr. Frank Back of the Zoomar Corporation has published a scientific derivation of this formula[6]. This derivation is essentially the same as the one given above. Dr. Duncan McDonald has also derived it. Further, many callers and letter writers assure me that the formula checks out "right on the button." Many people claim more virtues for it than I ever did. Statistically speaking, one of the difficulties of combining linear motions with symmetric random resolution losses is the fact that linear motions of known direction correspond to a bias in data and probably should not be treated or averaged as if they are Gaussian. But this is a matter not requiring exposition at this point. The old simple reciprocal formula has educated a generation of workers in the relations between various components, and to an examination of limiting resolutions due to the printer, the atmosphere, motion, enlargers, film, reproduction materials and the rest. It shows how resolution cascades downward as we add components, and it directed attention to weaknesses in the chain.

As long as we are being historical, and picking up some loose ends

seldom discussed, I might point out that to my knowledge the first and earliest mention of the possible contributions of communication theory to photography was in a speech I gave at a symposium on reconnaissance in 1948. That speech, along with several other papers presented at the symposium, is now being republished by The RAND Corporation.[7] I said the following about these matters:[8]

> "The aerial photographer or photo-interpreter can, and does, ask embarrassing questions. He may say 'All this talk of resolving-power and lines/mm. leaves me cold. What I want to know is this. If my particular camera system will resolve say, 30 lines/mm., what detail can I see in the photograph of airplanes sitting on the ground?' This difficult question cannot now be answered with confidence; however, a program designed to answer such questions is being started. Various types of military material, such as trucks, aircraft, guns are being placed in the immediate vicinity of some resolution targets. The line targets will then be imaged close to the photograph of the assorted military objets d'art, and the correlation of lines/mm., with a given focal length lens, and ground detail will be established.
>
> "In spite of the numerous and not easily answered objections to the high contrast line target, it has served what may be its most important purpose--that of choosing the better of the two lenses or two camera systems. Independent of the validity of the number calculated by Eq. (1) there is enough evidence at hand to substantiate the statement that the serial grading of lenses by their photograph-making ability (as determined by experience) will not differ from the serial grading of the same lenses using the calculated average resolving-power.
>
> "Studies conducted by the N.D.R.C. during the last war, and similar studies pursued after the war, indicate that resolution is only part of the story. Microscopic detail contrast is also important, and is associated with the 'cleanness' of a photograph. It is well known that photographs exhibiting high resolution and good tonal separations in the small details, can be sorted out from poorer quality photographs without any optical aid except the eye, i.e., without actually examining the microscopic detail.
>
> "This matter is really quite sophisticated, and further

detailed discussion in this paper will lead us too far afield.

"A fresh approach may be to examine the actual nature of photo-interpretation. The writer feels that Professor Norbert Wiener's brilliant and provocative Cybernetics[9] can offer much help in the understanding of the psychophysics of photo-interpretation, and in the formulation of a new measure of information. This book is subtitled Control and Communication in the Animal and the Machine. The jacket carries the following interesting message (to which should be appended "and photo-interpreters"): 'A study of vital importance to psychologists, physiologists, electrical-engineers, sociologists, philosophers, mathematicians, anthropologists, psychiatrists, and physicists.' In Chapter VI (Gestalt and Universals, p. 156 ff.) Wiener discusses the problem of recognition of objects by their forms (our problem--what makes a photo-interpreter think that a little gray blob on a piece of flat paper is the image of a medium tank). Thad Jones[10] presents an interesting and relevant discussion on this recognition problem, describing the mechanics of recognition, by Mediterranean Theatre photo-interpreters, of loose scattered grain in photographs taken from 20,000'. Wiener describes the development of a statistical theory of information in which the unit of information is transmitted as a single decision between equally probable alternatives. This idea occurred to several people at the same time, according to Wiener: the English statistician R. A. Fisher, working in mathematical statistics; Dr. Shannon of the Bell Telephone Laboratories, in connection with information coding problems; and Wiener, in his work on noise and message in electrical filters. The analogy to our problem--of identification of large ground objects from small plane images of them (or in the case of stereo-viewing, from distorted spatial images) lies in the consideration of the mechanics of recognition of an outline; and Wiener shows that '...three-fourths of the fibers in the optic nerve respond only to the flashing "on" of illumination. We thus find that the eye receives its most intense impression at boundaries, and that every visual image in fact has something of the nature of a line drawing.'

"From a consideration of these stimuli, or decisions, Wiener shows that the amount of information, as he uses this concept, is related to the notion of entropy in classical statistical mechanics and thermodynamics. He finds that as the amount of information in a system is a measure of its degree of organization, so entropy of a system is a measure of the degree or disorganization of the system; hence amount of information is the negative of entropy. In Wiener's analysis, the information carried by a precise message in the absence of noise is infinite; in the presence of a noise, the information carried is finite, and approaches 0 as the noise

> increases. The analogy to the photo-interpretation problem of measuring the information in a photograph, would involve calling directional blurrings (motion, vibration) distortion. Poor contrast, fog, haze, and grain effects, are, in this analogy, noise.
>
> ".....Eventually, as the powerful methods of modern statistics, psychophysics and the related sciences (including cybernetics), are focussed on these engrossing problems, we may expect genuine advances. The writer has been presenting speculative considerations only; perhaps someone can convert the speculative into the substantive."

## IV. THE PURPOSE OF TESTS

We should be very clear about the purpose of testing lenses and cameras, whether in the laboratory or in the air. We have to decide ahead of time for whom the tests are being performed, for this will determine their nature. For example: at Wright Field we never knew enough about lens design to be presumptuous enough to think that we could tell the designer what to do, based on the tests. We never told him how to re-design the lenses or how to improve them. Our tests were not designed for him. They were designed, if that is the right word at all, to have some relation to the picture-taking community out in the field--the aerial reconnaissance users.

Other laboratories during WW II used special star tests, the analysis of which was meaningful for them, and for the people they were reporting to. This may seem like a simple point, but unless it is stated clearly and admitted, it is indeed a source of much confusion and argument.

Another purpose of tests is as a quality control procedure, or, as is now more fashionable to call it, quality assurance work. Cameras and lenses being produced must be tested for compliance with

specifications, and for acceptance against standards.

In all of this, we must not forget that the ultimate consumer of the kind of images we have been talking about here is the photo-interpreter. He is truly the man for whom all this is being done. It is important not to forget him, not to make assessments which exist in a rarefied atmosphere all their own, and that are not grounded in the reality and meaning of the ultimate user.

If someone wishes to take exception to this, and note the existence of lenses, processes, picture-taking situations, where photo-interpreters are not involved, I say Amen. But that is not what I am talking about. I will keep insisting that this subject has its primary genesis in the requirements for aerial photographic images of high quality and their users.

To be meaningful, a test has to meet several simple criteria. (These points may seem obvious, but I can assure you that they are often forgotten and neglected in practice.)

First, the test must be duplicable. Different laboratories, different installations, and different observers must get substantially the same result when the test is repeated. The test has to be capable of being described in words, and should embody apparatus, and use procedures that can be available in more than one spot.

Second, the test must show as significant, differences that are really significant as measured by the ultimate test of the interpreter.

Third, the test must grade lenses or cameras in the correct order. It must not only show significant differences, but when they are shown

to be in one direction in the test, they must come out in the same order in actual use.

## V. ABOUT THE PHOTO-INTERPRETER

I could have slipped the following material in, and I'm sure only a few readers would have seen through the fact that this comes from some remarks made in 1951[11]. I am reprinting them here because I would hardly say anything different today about the subject. Such tempering, such footnotes as I will put on, will be put on later.

> ".....I notice that a number of people have been gleefully trying to kick the three-line resolution target to death. I want to point out again--and I have done this in other meetings, that it has served its purpose well. This purpose, simply stated, is to serially grade lenses in a manner that will correlate with their photograph-making rank. I have yet to be shown that our use of the three-line target in the judging of lenses to be used for aerial photography has led to any error, let alone consistent error...
>
> ".....But how about the difference between two lenses that have the same AWAR? Suppose we have a lens whose resolution varies from 40 lines/mm at the center to 10 lines/mm at the edge of its field, and that the average is 20 lines/mm. Let us say we have another lens that varies from 22 to 18 lines/mm, center to edge, and that also averages 20 lines/mm. Which lens is preferable, assuming uniform probability of occurrence of objects of interest in all parts of the field? I strongly suspect that we really want the second lens...
>
> ".....Other questions dealing with evaluation of two lens systems are even more complicated. Suppose for Air Force purposes, we have, let's say (with our test, which can be disputed the rest of the evening of course) a lens that will average 22 lines/mm with the film used in aerial photography. Let's also suppose it weighs three times as much and costs ten times as much as another lens of the same focal length and angular coverage, but that the second lens averages only 14 lines/mm. (By the way, we never seem to be faced with the converse of this situation. Here's a good problem for the lens designers.) Let's further suppose that the detail we're interested in is caught with the lighter, cheaper, lower resolution lens perhaps but 10 per cent of the time it is used, but the better lens records this detail in interpretable form

90 per cent of the time it is used. How then compare the value of the lenses?...

".....From this standpoint it is clear that relative figures of 9 to 1, or some function of these figures, is more reasonable than actual cost or resolution figures. I am not throwing these out as answers but am only suggesting that there are large numbers of questions that are unanswered, even after resolution figures or other performance indices are given. Unfortunately, the more we learn of this business, the more questions arise. Progress here seems to lie in the direction of awareness of relevant questions...

".....I also feel strongly that we are really looking for some measure of the information content of an optical (or photographic) image. This question has not been thoroughly explored, and as far as measuring information content, I feel that all proposals--U. S. Air Force resolution measurements, Howlett's doughnuts, Cobb Charts, Eastman's acutance, etc.--while clearly having some relation to information content, are equally poor measures of information content. This is no criticism of these interesting systems. They weren't supposed to measure information content, and they don't. I think this may well be a fruitful area for careful investigation..."

In a hurry to get to technical symposia to discuss things among ourselves, to build instruments for evaluating, measuring, and, indeed to build better systems, lenses, cameras, films, etc., we tend to forget the poor interpreter.

In a paper written more than ten years ago[12] I discussed the photo-interpreter at length. Let me construct an example which I have had occasion to use many times in the last few years, and which, hopefully, will illustrate the fundamental features of interpretation and image evaluation. Suppose I invited a photo-interpreter from the Royal Netherlands Air Force to the United States, and gave him a picture of an American city. Suppose that on this photograph, made at comparatively low altitude and large scale, was an image of a ground object, the image being perhaps half an inch square. Let us assume

further that the photograph was of high resolution. Let's take a median number, say 50 lines per mm. There is no question here of threshold effects, or of having but two or three lines across the object. No matter how one figures this, the number of bits of information in this piece of overall photograph is of the order of several million bits. Now to make a long story quite short, our friend, the foreign photo-interpreter, could look at this object for weeks on end, and, until someone told him in words, he would never be able to decide that this was an outdoor movie theater. In other words, an object outside his own experience, something that he doesn't have a name for, cannot be interpreted--the meaning of the image can't be evaluated from an aerial photograph. By the same token, once he understands the mechanics, theory and practice of outdoor theaters and their general construction, he would be able to identify an outdoor theater when the image area is perhaps 1/1000th that of the original photograph which he was unable to identify. Clearly, there are factors at work here that are non-numerical, that have to do with context, and with outside information. Shakespeare put it more directly in Act I of Hamlet:

"There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy."

## VI. CONCLUSION

Let's get back to the main stream. What about modulation theory, the Fourier transform, sine-wave response, transfer functions--all of which, for practical purposes, are the same way of expressing the

variation in contrast rendition of the system as a function of the frequencies impressed on the system. Let's face it, we might as well stop fighting the tide. The tide is coming in; these techniques are here and by and large are good. My earlier simplistic remarks about the fact that the three-line target always seemed to give us the right answers may not always be true in the future, when we may be dealing with lenses of complicated geometry, with annular obstructions, such as are found in various kinds of catadioptric systems. Odd things can happen, and no doubt will, with lenses of this type.

Besides, from a strictly professional standpoint, this stuff is all very good. It makes for symposia, meetings, arguments, and speeches, and enables various people to write theses and produce a bibliography. Above all, it is good for the economy. It used to be that we could hire school kids to test lenses; they are now being replaced by Ph.D.'s, armed with hundreds of thousands of dollars worth of equipment. That these new methods may be useful in design seems already established. However, I suggest they will much more likely be an aid in report writing and proposal preparation. G. Brock tells me that Wild, who produced the well known and highly regarded Aviogon and other lenses, uses only a high contrast three-line target. Apparently, it doesn't hurt.

If we look at various bright meteors that have streaked across the scientific skies in the post-war years, and see how they have done, we may have a clue to the likely future of contrast function analysis and sine-wave response theory in this business. Information theory was very big after the war, and many people thought many problems would be solved. It does not seem to have borne out its promises,

although it is certainly true that information theory has produced much insight, yielded new words and a useful terminology, and interesting ways of looking at things.

How about the Theory of Games? This excited much interest some years ago, but I suggest that the number of workers actively pursuing it is sharply diminished. Game Theory is, of course, a fascinating mathematical exercise, and it too has produced many insights, some new nomenclature, and ways of looking at problems. As a result, it has been beneficial although it, like other meteors no longer in orbit, has calmed down and cooled down.

Operations research? Systems analysis? Communication theory? Cybernetics? All started rising, and then settled down to respectability without ever fulfilling the promise and revolution that their backers and early enthusiasts thought. So relax, folks, work with sine-wave response, but just as a caution, keep the three-line target around; we may need it again.

There is an old biological saying: "Ontogeny recapitulates phylogeny." What this statement means for our science is that individual workers have to go through these developments by themselves, and cannot easily depend on conventional ways of learning from their predecessors. I have no fear that things will come out all right.

What is important, and what we sometimes overlook, is that lenses are getting better, photographs are getting better, and so with mmon resolution we proceed to higher resolution.

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