Norwood's dome: a revolution in incident-light photographic exposure metering

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Issue 3
October 9, 2022

ABSTRACT AND INTRODUCTION

In the late 1930's, Donald W. Norwood introduced a new principle of incident light photographic exposure metering in which a translucent hemispherical shell (a "dome") collects the ambient light incident on the scene for measurement by a photoelectric cell. It was found that exposure meters following this principle could, with a single measurement, consistently develop an exposure recommendation that would be highly appropriate over a range of lighting situations, especially those of interest in cinematography and portrait photography.

Today, the preponderance of exposure meters exploit Norwood's principle in their basic configuration for incident light exposure metering..

But it is not at all obvious, even after considerable study, just how and why meters following Norwood's principle give this widely-acclaimed performance. In this article, we will look "under the dome" and see just what is going on.

Background is given in various pertinent aspects of the topic of exposure metering. Appendixes discuss in detail various pivotal technical issues.

1 EXPOSURE METERING

1.1 The concept

In exposure metering, we use a special instrument which determines either the average luminance of the scene to be photographed or the illuminance of the illumination on the scene, and from that (along with the known or assumed sensitivity of the film or digital sensor system in use) provides us with an *exposure recommendation*. By that we mean a continuum of combinations of exposure time (shutter speed) and aperture (as an f-number) that would all produce a certain photometric impact on the film or sensor. Our aspiration is that by using that exposure recommendation for our "shot" we will attain the desired *exposure objective*.

1.2 The exposure objective

What do we mean by *exposure objective*? The "scene" being photographed, from an exposure standpoint (and let's assume a "monochrome" camera) presents to the camera as a mosaic of varying *luminance*, with a certain overall range. The lens transforms this into a mosaic of *illuminance* upon the film or sensor.

We would like the range of illuminance in that mosaic to be "planted" so that, in combination with some exposure time (shutter speed), the resulting range of *photometric exposure*[1] will fall in an appropriate place in the acceptable range of photometric exposure of the film or sensor.

But what is “appropriate”? There are several strategies we might adopt. Three commonly-chosen ones are:

A. Consistent average photometric exposure. Here we seek the average photometric exposure to be some established fraction of the saturation photometric exposure. This is the approach taken by basic “reflected light” exposure metering, which works from the average luminance over an field of view that ideally is the same as the field of view of the actual shot. It is not so much the result of a desirable “objective” but more of convenience in execution.

B. "Expose to the right" [2]. Here we seek to have the "brightest" spots in the scene receive a photometric exposure that is "close to saturation"—that is, close to the photometric exposure above which changes in photometric exposure do not result in very much change in the response. Attaining this generally depends on metering of the luminance of a spot on the “lightest” area of the scene.

C. "Reflectance-based" [3]. Here we seek to map the portions of the scene having different reflectances approximately onto proportional values of photometric exposure (on a scale that runs to 100% reflectance at the “saturation” photometric exposure).

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[1] *Photometric exposure* is the phenomenon to which the film or sensor responds, the product of the illuminance on the film or sensor and the exposure time.

[2] So called because "to the right" is the direction of increase in photometric exposure, exposure result, and such in various charts, histogram displays, and so forth.

[3] This very much follows the underlying concept of the Zone System, a doctrine of exposure planning devised and promoted by Ansel Adams and others.

Attaining this generally depends on measuring the illuminance on the scene ("incident light" metering).

A common parable for an important disadvantage of A is that, if we achieve it, the image of a "black cat on an coal pile" (nothing else in the scene) and the image of a "white cat on a snowdrift" will both look like a "gray cat on an ash pile."

An advantage of B is that the range of the film or sensor is best exploited with regard to such performance properties as dynamic range and noise performance. A common parable for an important disadvantage of B is that, if we achieve it, the image of a "gray cat on an ash pile" (nothing else in the scene) will look like a "white cat on a snowdrift".

An advantage of C is that, following the parable above, the images will reveal the various objects (cats, what the cats sit on) as we expect to see them. Stuff we know to be "gray" will in the image look "gray", regardless of the overall scene content; stuff we know to be "white" will look "white".

1.3 Reflected-light exposure metering

The earliest approach to exposure metering, still widely-used, is *reflected-light metering*. Here our instrument measures the average luminance of the scene (over a certain field of view, which may or may not closely conform to the field of view of the camera as it will be used to photograph the scene). We also feed into the meter an *exposure index*[4], which in basic practice today would be the advertised *ISO speed* of the film or digital sensor system. The instrument then gives us an *exposure recommendation* (defined earlier).

If we actually follow that recommendation in setting the camera for our shot, the result will be that the *average* photometric exposure on the film or digital sensor will be a fixed value (with reference to the sensitivity of the film of sensor).

This achieves exposure objective A, not really a desirable one. Then why do we use this metering technique? Because it is easy to do.

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[4] The term "exposure index" intimates a film speed value, not necessarily the rated film speed, used as an input to an exposure meter. It may be chosen as different from the rated film speed to cause an intentional offset to the *exposure recommendation* issued by the meter. I use this label for the input to the meter rather than "film speed" since there is no guarantee that the photographer will enter the actual rated film speed (if only for the reason discussed just above).

1.4 Incident light exposure metering

Here our instrument determines what we for the moment will describe as the *illuminance* of the light that is incident on the scene. We also feed into the meter an *exposure index*, discussed above. The instrument then gives us an exposure recommendation.

Ideally, if we actually follow that recommendation in setting the camera for our shot, we will attain exposure objective C. In the image, for each scene element, the relative luminance of the image will be that proportion of the maximum recordable luminance that is the reflectance of the scene element.

But in fact, if the illumination of the subject does not come uniformly from all directions, this tidy result will only be achieved if all surfaces of interest in the scene have the same orientation (are all parallel to a certain plane), and the incident illuminance is measured with respect to that plane.

That is hardly the case in most photography and cinematography. For a human subject, a small region in the center of the forehead is in a quite different plane than a certain small region on one cheek.

1.5 A further complication

A further complication is that often we do not really want to attain Objective C. A powerful example of why is if we photograph a spherical object of uniform surface reflectance (perhaps a decorative "matte finish" gray stone ball ball). If we perfectly attain objective C, the result will be as seen in figure 1.

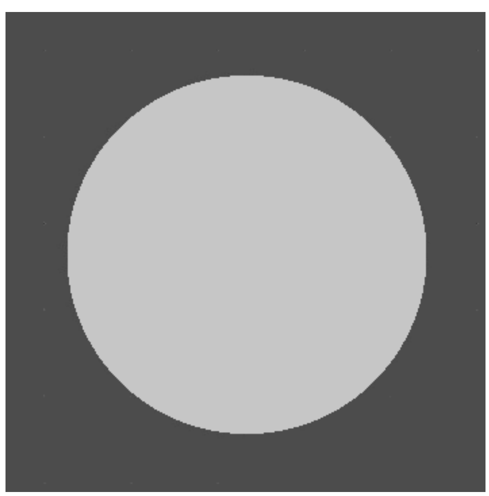

Figure 1. Sphere under uniform omnidirectional illumination

Here the "implied relative luminance" of the image of the sphere would ideally be (as part of objective C) the same as the reflectance of the sphere itself–uniform for the entire sphere (at least the part the camera can see).

But, sadly, that doesn't look so much like a sphere. We might expect a photo of a sphere to look like one of the images in figure 2 (taken under various illumination setups).

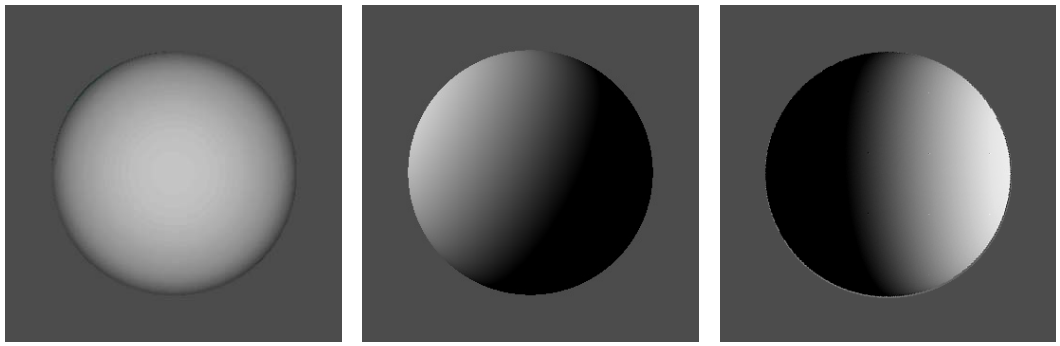

Figure 2 a, b, c. Sphere photographed under various illumination setups

And to attain any of these, we would have to use some scheme of illumination other than "uniformly omnidirectional".

Now, to get a little ahead of the story, let's imagine three scenarios in which the photographer uses one of the three lighting plans represented in these images. Now for each one, what would be the "ideal" exposure result? If we knew that, then we could think in terms of some metering technique that would lead us to the photographic exposure settings (combination of aperture and shutter speed) that would give us that exposure result.

Well, our objective can't be the tidy one expressed under C, above. That objective would be attained with an image that looks like that in figure 1, and we decided that wouldn't be very desirable.

And in fact, there is no "tidy, automatic" way to conclude what exposure result would be "ideal" for one of our sphere photos—that would be a matter of the artistic judgment of the photographer. For example, maybe some of the ones in figure 3 would be "better" than the corresponding ones in figure 2. Or maybe not.

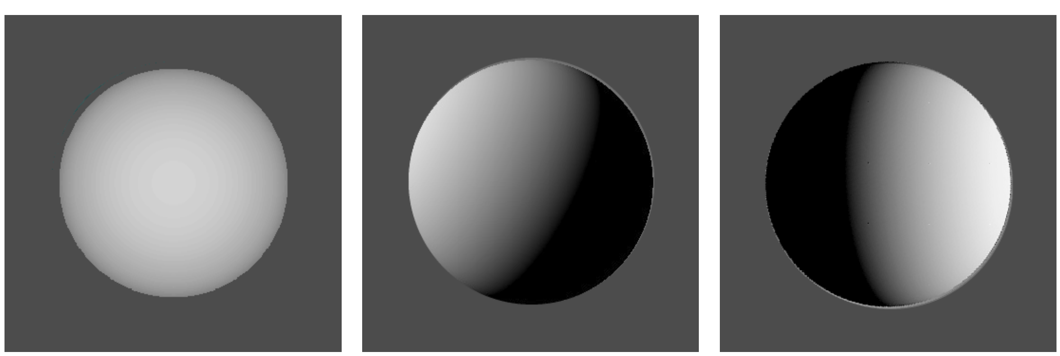

Figure 3 a, b, c. With a greater exposure

Hold that thought.

1.6 Cinema/portrait lighting technique

Typically in close-up cinematography and in portrait photography, as with the sphere in our example, we rarely want an image resulting from the use of uniform omnidirectional lighting. Rather, we will generally want to use a more sophisticated lighting technique that will "sculpt" the features of the subject.

Very often, in this situation, the subject of the shot is illuminated by two light sources, under the so-called "key-fill" technique. The *key light* is typically directed to the subject from the side. It serves to create shadows that "sculpt" the face. The *fill light* is often (but certainly not always) directed to the subject from near the camera position. Its job can be looked at as "diluting" the shadowing from the key light to retain just the degree of sculpting desired by the cinematographer or photographer.

Figure 4 shows an example of relatively severe "sculpting" on the model's face and a lesser sculpting on her torso.

Figure 4. Sculpting

The result of course departs dramatically from the premise of Objective C, which is that in the final image, the illuminance of each element of the image is proportional to the reflectance of that element. With the lighting technique I mention above, the left cheek of our subject may have a high reflectance, but we intentionally light the subject so the left cheek is "in shadow", and is thus given a low luminance in the image.

What should be our objective for the "distribution" of photometric exposure over the image in such a case? As with our little exercise in photographing the stone sphere, there is no simple answer. (This is a dilemma we will encounter repeatedly in this area of study.)

Thus clearly we cannot devise an single exposure metering technique that will, on a theoretical basis, deliver the "ideal result", since we can't even define what that would be.

1.7 Duplex metering

Nevertheless, faced with this conundrum, over the years cinematographers (and portrait photographers) found, empirically, that an exposure result in the image that they considered "desirable" could usually be attained by what came to be called the "duplex" technique of incident light exposure metering.

Here, an incident light exposure meter is used to take separate readings while its receptor faced the two principal light sources. The average of the two meter readings is used as the input to the exposure calculator on the meter to develop the exposure recommendation.

Is there some theoretical model that can suggest why this works in what is often considered a "desirable" way? No.

2 THE NORWOOD PRINCIPLE

2.1 Donald W. Norwood

Donald W. Norwood had been a photographer in the US Army Air Corps in the period after World War I, and had in fact during that service devised some improvements in photographic processing. After he left the service, it seems as if his attention was directed to cinematography (although it does not seem that he actually practiced that craft professionally).

2.2 Incident light exposure metering in the mid-1930s

In the mid-1930s, incident light metering had become common in cinematography, as is was seen as leading to the "most consistent" results over a range of scenes. Typically, when multiple source lighting (for example, key-fill lighting) was used, the "duplex" metering technique (see section 1.7) was used, requiring two or more measurements to be used to prepare for each shot, a burdensome matter where "time was money".

2.3 Norwood's vision

Don Norwood, pondering this inconvenient situation, had a vision of a scheme by which a single measurement would directly give an "appropriate" exposure recommendation over a range of key-fill lighting setups.

The scheme revolved around a measuring instrument in which the photosensitive element had the form of a hemisphere (as contrasted to the "flat" photosensitive element typically used theretofore in incident light exposure meters). He later realized that the same behavior could be attained at less manufacturing cost by using a translucent hemispherical "light receptor" (a "dome") mounted over a conventional flat photosensitive element.

Norwood received a patent on this system in 1940.

2.4 A great success, to this day

Work done with prototypes of exposure meters following Norwood's principle seemingly gave highly satisfactory results, and soon commercial meters (made under Norwood's patent) were "all the rage" among cinematographers.

Figure 5. Norwood Director exposure meter ("Model A")

In figure 5, we see the first "Norwood Director" exposure meter, made, under Norwood's patent, starting in 1947. (The design work had started in 1941, but the company became devoted to the war effort, which delayed the completion and release of this product.) This product came to be called, by meter aficionados, the "Norwood Director Model A", even though that model designation was never used by the manufacturer.

We can hardly miss the "dome" (actually about 1.5 inch in diameter).

A short while later, a second manufacturer was also licensed under Norwood's patent, and developed the meter we see in Figure 6 (introduced in 1948). It also carried the name "Norwood Director", and was identified as "Model B" out of respect for its progenitor, often called the "Model A" (even though that was made by a different company and that designation was never official).

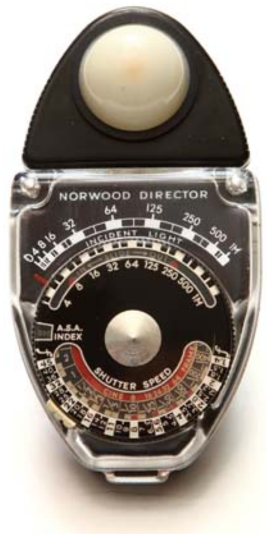

Figure 6. Norwood Director Model B exposure meter

From the collection of Carla and Doug Kerr
Photo by Douglas A. Kerr

This widespread acceptance of Norwood's principle has continued to this day. Almost every incident light exposure meter made today follows Norwood's principle, which we can easily recognize from the prominent white domes they all sport. We see a typical modern such meter, this one digital, in figure 7.

Figure 7. Sekonic Model L-408 exposure meter

Photo by Kyu Hachi

In fact one of the many models made by Sekonic today—in the vein of a "classic"—is almost identical to the meter seen in figure 2, which was designed at least 60 years earlier. We see this later model in figure 8.

Figure 8. Sekonic Model L-398A exposure meter

From the collection of Carla and Doug Kerr
Photo by Douglas A. Kerr

Sadly, this is likely the last of the "direct descendants" of Norwood's original meter. But the dome lives on.

3 BUT HOW DO IT KNOW?

3.1 A photometric model?

Understandably, upon the emergence of the Norwood-type meter, engineers and scientists interested in this area were anxious to recognize a model, based on known principles of photography and photometry, that would explain how and why a "Norwood" meter could consistently yield exposure recommendations that were felt to be "highly appropriate" over a range of lighting situations.

This quest for insight was greatly burdened by the fact that we had no objective "metric" by which we could judge the "appropriateness" of the exposure result in an image, and thus objectively score how "appropriate" was the recommendation of the exposure meter.

3.2 No real help from Norwood

Those seeking to develop such a model got little help from Norwood, who for many years did not offer any technically-meaningful "rationale" for the working of his system. (He later suggested that this reticence was because the protection of his principle by patents was not yet complete.)

In fact, the only early insight into the rationale comes from this introductory passage in Norton's definitive patent on his system, issued in September, 1940:

> "One of the particular objects of the invention is to provide an exposure meter which is substantially uniformly responsive to light incident upon the photographic subject from practically all directions which would result in the reflection of light to the camera or other photographic register."

Now this sounds nice, but is not too helpful in understanding why this should lead to the useful performance we associate with Norwood-principle meters. And in fact (as we will see later) it is not even true. The theoretical response of a hemispherical "receptor" is not uniform from all directions of interest, but rather declines with increasing angle of arrival of the light, following a mathematical curve known as the *cardioid*. The derivation of this is given in Appendix B.

But it certainly possible that early in his work, Norton assumed that the response of a hemispherical receptor meter would be uniform from all directions (at least all directions of interest). Later, in a seminal paper (discussed in Appendix A), we find him expressing a different (but still not quite correct) view of the expected response of a hemispherical receptor.

3.3 An elaboration of that outlook

Not too long after the introduction of the Norwood system meter, Norwood pointed out that the hemispherical light receptor was a approximate proxy for the human head—that is, the part of it that can be seen from the camera. If we follow the photometric trail (based on the notion of uniform sensitivity of a hemispherical-receptor meter for all angles of arrival), that means that the meter reading would indicate the average[5] illuminance on the part of the subject visible to the camera.

This notion was elaborated upon in a paper by Norwood published before the Society of Motion Picture and Television Engineers in 1941 ("Negative Exposure Control", *J SMPE 1941, 36:389-402*), which (among other things) was intended to give a rationale for the working of the hemispherical receptor incident light exposure meter

But seductive as this model sounds, it still leaves us with the question, "Why would an exposure based on the average illuminance on the part of the subject visible to the camera lead to an 'appropriate' exposure result (whatever that is) for a range of lighting setups?"

3.4 Something more "scientific"

In 1950, perhaps in response to continuing pressure from the community for a "scientific" explanation of his principle, Don Norwood

[5] Average by surface area, to be precise.

published a paper before the Society of Motion Picture and Television Engineers ("Light Measurement for Exposure Control", *J SMPTE 1950, 54:585-602*) that gave a helpful outlook into that mystery, not through an abstract mathematical model but rather through analysis of empirical observation in a test program. The presentation has a number of (to me disappointing) lapses of rigor (perhaps even of candor), but fortunately these do not invalidate the practical conclusion.

I discuss (and critique) this paper in some detail in Appendix A.

Briefly, Norwood found that, in a key-fill lighting setup, for a given angular position of the key light, there was a certain exposure setting (greater than the exposure used for a metered reference shot with the key light at the camera) which produced an image which observers adjudged to be "comparable in exposure result" to the head-on lighting reference shot (whatever "comparable" might be).

Norwood then went on through several stages to purportedly demonstrate that the response of a hemispherical-receptor meter *vs*. the angle of the light hitting it [6] would be such that the meter would give an exposure indication that would exactly be the exposure which the subjective tests had shown was needed to produce a consistent "visual appearance of exposure" of the image.

Sadly, the development of this conclusion is burdened with the kind of gaffes that would probably have caused the paper to be sent back by any credible peer review board. I describe these gaffes in Appendix A.

But the good news is, despite the lack of forensic credibility created by these gaffes, the ensuing numerical discrepancies are not probably large at all, and overall this paper still demonstrates that the readings of a Norwood system meter are a good practical guide to exposure over a range of situations of key-fill lighting—possibly even over a far wider regime of photographic lighting situations.

4 COMPARISON WITH THE "DUPLEX" TECHNIQUE

We started by pointing out that, prior to the emergence of the "Norwood" metering concept, the "duplex" technique was often used to develop an exposure recommendation in such cases as key-fill lighting. Seemingly, there was general satisfaction with this technique, other than that it was time-consuming.

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[6] This is technically referred to as the *directivity pattern* of the meter.

The Norwood system allowed the exposure recommendation to be determined with a single measurement, clearly an improvement in efficiency.

It is then interesting to ask, "For a given key-fill lighting setup, would the duplex technique and a Norton system meter theoretically yield approximately the same exposure recommendation?"

Yes. Table 1 gives the results of a simulation done here, comparing the exposure recommendations developed with the duplex metering technique (assuming an exposure meter with *cosine* directivity) and an ideal "Norwood" meter (with *cardioid* directivity[7]). The assumed key:fill ratio is 8:1 (as in Norwood's paper).

The relative exposure recommendations are shown first as the actual relative numerical value, followed (in italics) by the equivalent in stops.

Key light angle	Relative exposure recommendation (duplex)	Relative exposure recommendation (Norwood)
0°	1.00/*0.00**	1.00/*0.00**
45°	1.17/+*0.23*	1.15/+*0.20*
90°	2.00/+*1.00*	1.80/+*0.74*

* By definition

Table 1.

As you can see, the agreement between the two techniques is quite good in this case. The agreement declines for greater key light angles and (although not shown here) declines for smaller key:fill ratios.

5 RECOGNITION

Norwood's introduction of the hemispherical receptor exposure meter, almost certainly at first based more on intuition than scientific principle, made a gigantic and long-lasting improvement in the art of incident light exposure metering, initially especially in the cinematographic arena. It seems quite fitting that, in April, 1969, he was given an Academy Award for this work.

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[7] The directivity theoretically exhibited by a hemispherical receptor meter. This is not the directivity posited by Norwood.

6 GENERALITY?

Norwood tells us that a light source located at an angle from "head on" has an "effective illumination factor" that decreases linearly with the angle, starting at 1.0 at 0° and reaching 0.5 at 90°. "Effective" refers to the influence of the light on the visually-perceived overall exposure result.

When the light is where its effective illumination factor is 0.5, then we need to use twice the exposure we would need if the same light were where its effective illumination factor was 1.0 (at 0°) in order that the overall visual impression of exposure would be the same on the images taken with the two lighting situations. Fair enough.

But, so far as we can read in Norwood's paper, this particular "effective illumination factor" as a function of angle was only observed in the situation in which one of the lights (the "fill light") was at 0° and it had a luminous flux 1/8 that of the other light (the "key light").

But is that effective illumination factor function universal, over situations where neither light is at 0°, and over situations in which the ratio of the luminous flux density of the two lights was other than 1:8 (and in fact, in situations in which there are more than two lights?

We cannot answer that analytically, since we are dealing with the visual perception of "the same overall exposure" between images in which the shadowing of the subject's features are not consistent, and how that difference in shadowing affects the observer's perception of "overall exposure" cannot be modeled.

Yet the recommended usage of meters based on this principle is usually general. And, from the seemingly-broad acceptance of Norwood-system exposure meters over the years, we must assume that this generality is at least approximately in effect..

And note that whether or not this at least approximately true may well have been obscured, over the years, by the fact that, as is widely recognized in photography, no metering system of this simple type can always produce the "desirable exposure result", even if only because there is no universal metric for "how desirable" is the result (from an exposure standpoint) on a particular image.

7 MEASUREMENT OF ACTUAL ILLUMINANCE

In certain cases (some photographic, some not), we may wish to use our exposure meter to determine the actual luminance on a surface (Not what the implies as an optimal photographic exposure setting). After all, It has most of the necessary ingredients to do that. Three common such situations are:

- In some photographic situations, it is known that a "better" exposure recommendation will be gotten by measurement of the actual illuminance on the subject rather than with a "Norwood" measurement. The classical example is when the subject is the (flat) wall of a barn.

- When we wish to determine the ratio between two photographic light sources, which is best done in terms of the actual luminance they would deliver on a surface perpendicular to their direction from the subject.

- Wholly outside of photography, in such situations as verifying that the illuminance on an industrial workbench was at least the amount recommended for the type of work being done.

Determining illuminance rigorously requires the meter to have a *cosine* directivity pattern.

Essentially all exposure meters in the Norwood Director series provide for this by having an alternate receptor, this one generally in the form of a disk, which can be put in place by the user instead of the dome receptor.

Here we see both the receptors on a Sekonic L398A meter, the dome on the left, the disk on the right..

In other exposure meters (such as many of the Sekonic digital exposure meters, including the one seen in figure 7), the dome can be pushed down to play a role in a complicated structure that essentially has a cosine response.

There are a number of wrinkles in the matter of illuminance measurement, which are covered in Appendix E.

8 APPENDIXES

Appendix A. Norwood's 1950 SMPTE paper

Appendix B. Derivation of the cardioid directivity of the hemispherical dome

Appendix C. Typical actual directivity pattern

Appendix D. The conundrum of the two values of C

Appendix E. Measuring illuminance and the "footcandle" scale

Appendix F. Photometric evaluation of specimen Sekonic L-398A meter

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Appendix A
Norwood's 1950 SMPTE paper

A.1 INTRODUCTION

In 1950, perhaps in response to pressure for the industry for a technical presentation of the rationale behind his "dome" exposure meter, Donald W. Norwood published a paper before the Society of Motion Picture and Television Engineers (SMPTE) ("Light Measurement for Exposure Control", *J SMPTE 1950, 54:585-602*) that gave a helpful outlook into the way in which the hemispherical-receptor exposure meter gives appropriate exposure recommendations over a range of lighting situations.

It did this not through an analytical model but rather through analysis of empirical observations in a test program.

The presentation has a number of (to me disappointing) lapses of rigor (perhaps even of candor), but fortunately these do not invalidate the practical conclusion.

A.2 THE TEST PROGRAM

A.2.1 Introduction

The cited paper presents a "demonstration" of the working of the "dome" exposure meter through the analysis of a test program involving subjective comparison of prints made from a carefully-controlled series of test exposures.

A.2.2 The overall scheme

The test program pertains solely to photography of the human face using key-fill lighting technique (certainly a preoccupation of cinematographers as well as portrait photographers, then and now).

In the tests, for each of several human subjects, shots were taken with a key-fill lighting setup, with both light sources delivering consistent illumination on the subject at a key-to-fill luminous flux density ratio of 8:1. The key light was placed at angles (from the camera) of 0° ("head on"), 45°, 90°, and 135°.

The exposure settings used for the "head-on" shot with the key light at 0° was based on measurement, with that lighting setup, of the composite illuminance on a camera-facing plane at the subject, using a basic incident light exposure meter following the generally-accepted incident light exposure metering equation (albeit with the value of the calibration constant, C, for the meter not mentioned).[8] I will call this the "reference shot".

Then, for each subject, the key light was moved successively to the other positions. For each position, several shots were taken with various levels of exposure greater than that used for the 0° shot. We do not know the increment in exposure used between these shots, but suspect it was 1/2-stop.

Presumably, the film was all developed in a standardized way and prints made with a standardized exposure in the enlarger.[9]

Then, for each series of shots for a certain subject at a certain key light angle, a group of observers were asked which shots best "matched in appearance (in the sense of exposure) the reference shot of the same subject.

Here we run into a problem. Clearly none of the side-lit shots would truly match in appearance any of the reference shots, as the "sculpting" of the face would be quite different.

We have no idea what the instructions to the observers actually were in this regard. Perhaps the observers were actually asked which of the side-lit shots "looked to have the same overall exposure result as the reference shot", or perhaps, even better, "looked to have an overall exposure result that was 'equally as appropriate' as that of the reference shot", or maybe even "equally nice".

For conciseness in the reminder of this appendix, I will consider the property that the observers compared as the "visual impression of exposure result" and abbreviate it as "VIER"

A.3 ANALYSIS AND INTERPRETATION

A.3.1 The basic concept

In any case, statistical analysis of the response data led Norwood to the conclusion that, over the range of subjects used, the average exposure required in a side-lit shot to get the same VIER as that of the reference shot was consistently greater than the meter-indicated exposure for the reference shot by an amount that increases consistently with the angle of the key light.

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[8] Which would approximately fulfill "objective B" as expressed in the body of this article.

[9] I assume. Norwood does not trouble us with such details.

The degree of that needed additional exposure is shown in column 2 of table A1 (in the form stated in the paper) for the four key light locations used in the test program:

1. Key light angle	2. Needed additional exposure (stops)	3. Implied relative effective illumination
0°	0*	100%*
45°	½ –	75%
90°	1	50%
135°	2	25%

* By definition

Table A1

The entry for 45° presumably means "a little less then 1/2 stop". (To match the value in column 3 it would have to be about 0.42 stop.)

Norwood says we can consider this behavior as that the contribution of the key light to the attainment of a consistent VIER (which he calls its "effective illumination") declines with an increase in the angle at which the key light was placed. This outlook is shown in column 3 of the table. We can think of this value as the *effective illumination factor* for that key light angle.

He then says that if the relative response of the exposure meter, as a function of the angle from which the light arrives, follows that pattern of decline, then the exposure indicated by the meter will take into account this variation in the effective illumination from the key light, and the exposure recommendation will be the "appropriate" one for that lighting situation.

Column 4 of Figure A2 shows that needed directivity of the meter.

1. Angle	2. Implied relative effective illumination	3. Needed relative meter reading	4. Needed meter directivity
0°	100%*	100%*	1.00*
45°	75%	75%	0.75
90°	50%	50%	0.50
135°	25%	25%	0.25

* By definition

Table A2

A.3.2 That pesky fill light

A.3.2.1 *Introduction*

The entire motivation for Norwood's work was to seek a way to take a single exposure meter reading that would, in the case of a subject illuminated by both a key light and a fill light, indicate the "appropriate" exposure.

In actual photographic practice, the ratio between the illuminance of the key light and that of the fill light may be varied. A relatively more potent fill light serves to further "dilute" the shadowing from the subject's features cause by the key light being off to the side. The photographer will chose the key:fill ratio so that "diluting" produces the artistic result he desires.

The test program that "disclosed" the concept of the effective illumination of light arriving from an angle invariably used both a key light (at a variable angle) and a fill light ("head-on"), with the two always having a consistent ratio in the illuminance they delivered (8:1 for key:fill).

A.3.2.2 *Review of the test program*

For each subject, the process began with a "reference shot" with the key and fill lights having their standard "potency" and both located at 0°.

Then, for each angle of the key light a number of shots were taken with different exposure settings. The panel of viewers considered those multiple shots for the given angle and concluded which one was "most like" the reference shot as to VIER.

A.3.2.3 *The influence of the fill light*

For the key light at 90°, for example, the "average" viewer reaction was that a shot with 1.00 stop exposure greater than for the reference shot produced an image that was "most like" the reference shot as to VIER.

We can think of this as indicating that the overall visual exposure result cased by the new light setup was 1.00 stop "less hot" than the overall VIER for the reference shot.

In turn, Norwood then tells is that from this we can conclude that the key light at an angle of 90° gave an effective illumination of 1.00 stop less than when it was at 0° (that is, 50% of its value at 0°).

But there is a flaw in this rationale. Consider again the case in which th key light had been moved to 90°, and we find that an exposure of twice that for the reference shot was needed to give an equivalent VIER.

For the exposure meter to call for twice the exposure, the stimulus to the of the meter movement would have to be half that that for the reference situation.

But the stimulus on the meter movement only partially comes from the key light. The rest comes from the fill light. And that stimulus is not changes when we move the key light to 90°.

Accordingly, the stimulus from the key light must fall to less than half its value for the reference shot. Thus, the meter directivity at 90° would have to be less than 0.50 (about 0.43, actually). This is of course not a great discrepancy.

But if the key:fill ratio is less than 8:1 (4:1 and even 2:1 ratios are commonly used), this discrepancy becomes greater. We cannot quantify this greater discrepancy analytically, since we don't know how the different visual impact of these greater fill light contributions affects the observers' opinion of how much more exposure is needed to retain the same VIER as that of the reference shot.

For example, for a key:fill ratio of 4:1, we cannot be sure that, when we move the key light to 90° that the observers would feel than an increase in exposure of one stop would be needed to retain the same VIER (as was found to be the case with a key:fill ratio of 8:1.

A.3.2.4 *Disposing of these concerns*

Norwood does not discuss this matter directly in the part of his paper devoted to the "dome receptor" meter. But earlier in the paper, as he discussed exposure metering broadly, he makes this observation: "The fill-light is useful and necessary to achieve acceptable pictures but is distinctly secondary in exposure control matters."

He may rely on this in disposing of the discrepancy I discuss above.

I am not wholly impressed by that assurance. For one thing, even if the key:fill ratio is 8:1, with the key light at 90° (still assuming a meter directivity there of 0.50), the effective illumination afforded by the fill light would be 0.25 times that of the key light (which we can think of as adding "0.3 stop" to the overall stimulus on the meter.

For lesser key:fill ratios (4:1 and 2:1 are commonly used in still portraiture), the effective illumination effect afforded by the fill light would be an even greater fraction of the total effect. Again with the key light at 90° (still assuming a meter directivity there of 0.50) and a 2:1 key:fill ratio, the fill light would contribute fully half of the total stimulus on the meter. That would substantially disrupt Norwood's derivation of the needed directivity of the meter. But again, we cannot analytically quantify that.

A.3.3 The directivity of the meter

Recall first that Norwood, at this point in the story, is (correctly or not) looking for the meter directivity function to be that which we describe as the *Archimedean spiral* function.

Norton then looks into the theoretical directivity of a meter with a hemispherical receptor (which his intuition had initially told him was what is needed here). "By inspection" he (correctly) observes that for an angle of incidence of the light of 90° to the "peak" of the dome, only half of the dome would be illuminated. Thus, we would expect the meter directivity at that angle would be 0.50. Fair enough.

But he then just interpolates to conclude that for an angle of 45°, the theoretical directivity would be 0.75.

He then extrapolates the initial observation to an angle of 135°, concluding that the theoretical directivity there would be 0.25.

This directivity function, if plotted in polar coordinates, is a geometrical figure called the *Archimedean spiral*. Just what is needed.

A.3.4 No quite so

But this derivation is flawed. The derivation of the actual directivity function is given in Appendix B. That function, if plotted in polar coordinates, is a geometrical figure called the *cardioid*.

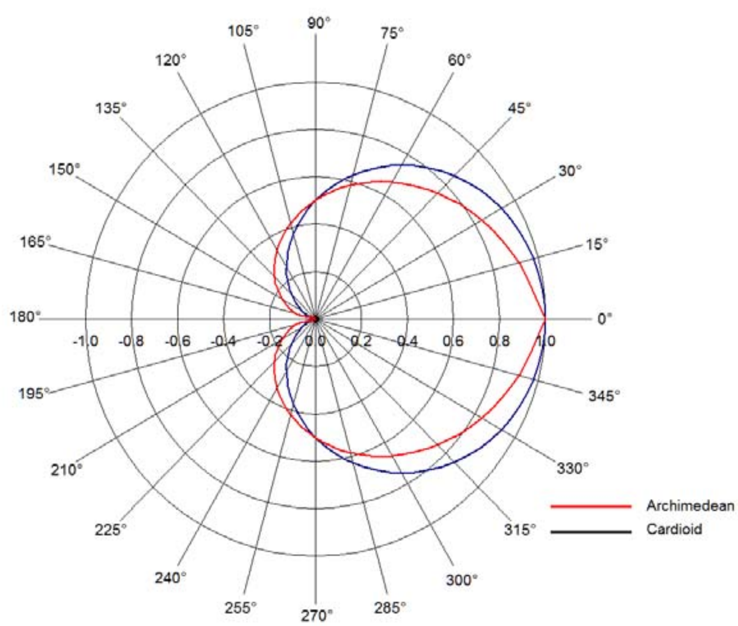

Figure 9. Archimedean spiral and cardioid directivity patterns

For comparison, we see in figure 9 these two functions platted in polar coordinates:

The difference between the two is greatest somewhere near 45°. At 45°, the value of the cardioid function is about 14% greater than that of the Archimedean spiral function.

This erroneous derivation of the theoretical directivity pattern of a hemispherical-receptor meter must be considered a flaw in Norwood's presentation. But fortunately, the numerical error is very modest.

A.4 THE WRAP-UP

A.4.1 Summary

In his paper, Norwood tells us:

1. With key-fill lightning, the optimal exposure (in terms of visual comparison of the result with the result of a "head-on" lighting setup) increases as the inverse of a linear decrease with the angle of the key light.

   Comment: I will accept that at face value.

2. The corresponding exposure recommendation will be given by a meter whose directivity decreases linearly with the angle of the key light. [That function is, if plotted in polar coordinates, an Archimedean spiral.]

   Comment: True only if we ignore the effect of the fill light on the meter (which Norwood assures us will be inconsequential.)

3. A meter with a hemispherical receptor will theoretically exhibit a directivity that decreases linearly with the angle of the key light. [That function is, if plotted in polar coordinates, an Archimedean spiral.]

   Comment: Such a meter will actually theoretically exhibit a directivity that, if plotted in polar coordinates, is an cardioid.

A.4.2 Grading the paper

The lapses from thoroughness and rigor in the trail of Norwood's "derivation" are intellectually disturbing, and might well have earned this paper an initial "thumbs down" had it been subject to peer review. And to the cynical forensic engineer (who, me?), they raise serious questions as to whether this story with its amazingly-tidy result was formulated in fully good faith by the author.

Did Norwood by any chance "work backwards" from a perfect result, taking artistic liberties with the mathematical relationships actually involved on the way? Or was he just uniformed, or careless with his work, and lucky as to his result? I leave it to the individual reader to contemplate that.

In any case, Norwood’s paper is a forensically-flawed demonstration of why a meter according to his design should be expected to consistently recommend an exposure that leads to an image result the photographer or cinematographer deems “good”.

A.4.3 The good news

That indictment aside, I first note that the actual lapses in Norwood’s presentation appear to likely have modest numerical impact. And in any case, we are speaking of a situation in which there is no “inherently exactly correct” result anyway.

Many years of actual use, often in the demanding regime of cinematography, of meters based on Norwood’s design have seemingly shown that the exposure settings indicated by these meters very often lead to an exposure result that the photographer or cinematographer deems “good”.

So, is it better to be lucky than rigorous?

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Appendix B
Derivation of the cardioid directivity of the hemispherical dome

B.1 THE DIRECTIVITY RESPONSE OF THE HEMISPHERICAL RECEPTOR

We assume that the "directivity pattern" of a hemispherical incident light metering sensor (including as implemented with a flat sensor covered by a translucent hemispherical dome) for light arriving from a given angle is proportional to the projected area of the dome as seen from the angle of interest. (That area determines, for a beam of any given luminous flux density, how much luminous flux the dome will capture and presumably pass in a consistent way to the sensor.)

B.2 THE PROJECTED AREA OF A HEMISPHERE FROM VARIOUS ANGLES OF OBSERVATION

We will work from figure 10.

<u>Panel a—"head on" observation</u>

In panel a of the figure, we see the projected area of the dome as we would see it from a point on its axis. Here Θ, the angle of observation, is 0. The cosine of Θ is 1.0. We use A to represent the projected area as seen from $\Theta=0$ (that is, as seen in this panel). A will mean that very same area in future panels.

In order to set the stage for our future work, I divide the projected area into two equal portions by a vertical dotted line. The area of each portion is A/2.

Note that in this case, the boundary of the projected area is in fact identical to the "rim" of the hemisphere as seen from our vantage point. Accordingly, in this view, the area of each half of the projected area of the hemisphere is of half the area of the circle defined by the rim of the hemisphere. This area is in turn determined by the radius of the hemisphere, *R*.

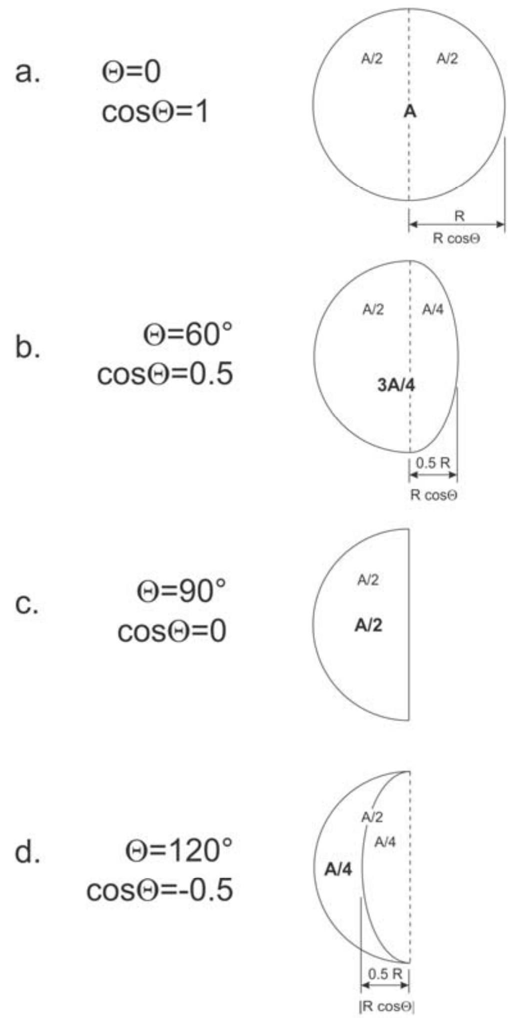

Figure 10. Projected area of the hemisphere

<u>Panel b— observation from an angle of 60°</u>

In panel b, we have moved our vantage point to the right by 60°, so that Θ, the angle of view of the hemisphere, is 60°.

The left boundary of the projected area is no longer the left half of the rim of the hemisphere, which has moved "around back"–just the leftmost "limb" of the hemisphere. But the right boundary of the projected area is still the right half of the rim, which has now moved "a bit to the front". That half of the rim is a semi-circle, but, since we see it from an angle to its plane, we see it foreshortened as a semi-ellipse, with a semidiameter that is cos $60°$ (0.5) times its actual semidiameter, R.

And thus the area itself is reduced by the factor cos Θ, to (A/2) cos Θ, or A/4. Thus the entire projected area of the hemisphere, the sum of the two sections, is 3A/4. (That area is shown outlined in bold.)

Panel c— observation from an angle of 60°

In panel c our view is from 90° to the right. We note that for $\Theta = 90°$, $\cos\Theta = 0$.

Now the "near half" of the rim of the hemisphere is seen "head on", and collapses to a vertical line; we do not see it.

Accordingly, the entire projected area of the hemisphere is just A/2.

Panel d— observation from an angle of 60°

In panel d, our view is from 120° to the right. We note that for $\Theta = 120°$, $\cos\Theta = -0.5$.

As in panel b, the right boundary of the projected area is the projection to us of the "near" half of the rim of the hemisphere, now "flipped" left of the dotted centerline. Again, its horizontal semidiameter is $R \cos\Theta$ (but, to be rigorous, since $\cos\Theta$ is negative, we must state that (positive) distance as the absolute value of $R \cos\Theta$).

Thus, the total projected area, A', is the "left portion" area, A/2, diminished by the area in the semiellipse, $(A/2) \bullet |\cos\Theta|$ (which comes to A/4), a net area of A/4.

Summary

We see that in every case, geometrically, the net projected area of the hemisphere is an area of A/2 to which we add an area of $(A/2) \cos\Theta$ (noting that for Q>90°, $\cos\Theta$ is negative, so that area then would actually be subtracted).

Algebraically, then, the projected area of the hemisphere from a point at angle Θ is consistently given by:

$$A' = \frac{A}{2} + \frac{\cos\Theta\, A}{2} \qquad (1)$$

or

$$A' = \frac{1 + \cos\Theta}{2} A \qquad (2)$$

Thus the relative sensitivity of the receptor, s, which we have assumed is proportional to the projected area of the hemisphere from the angle of interest, is:

$$s = \frac{1 + \cos\Theta}{2} \qquad (3)$$

But this is the expression, in polar coordinates, for a cardioid curve:

$$R = \frac{1 + \cos\Theta}{2} \qquad (4)$$

Quod erat demonstrandum.

B.3 IN REALITY

In an actual typical implementation, as soon as the angle of incidence gets beyond 90° there would be some obscuration of the dome by the meter housing. Thus we might expect for such greater angles the actual response would decline faster than as predicted by the cardioid curve.

B.4 GRAPHIC PRESENTATION

The theoretical response curve function (cardioid) derived above as plotted in polar coordinates (as a directivity pattern) is seen in figure 11.

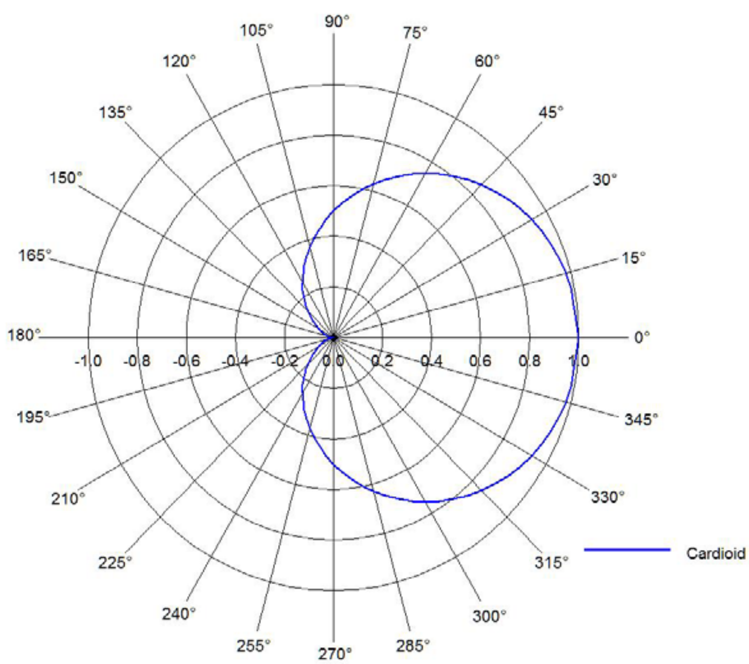

Figure 11. Cardioid directivity pattern

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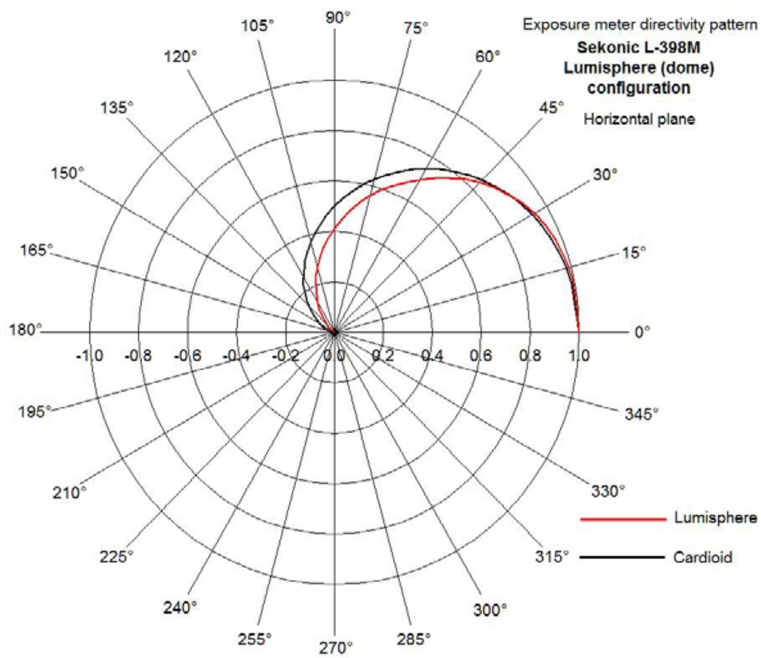
Appendix C
Typical actual directivity pattern

Field tests were made here [in 2014] of the directivity function of a Sekonic L-398M exposure meter in its "Lumisphere" (dome receptor) mode. This meter is a fairly recent member of the exposure meter line of succession that descended directly from Norwood's work.[10]

We see here that directivity function (in the by-now-familiar polar plot), along with the theoretical cardioid pattern for comparison.



We note that the pattern exhibited by the meter very closely follows the theoretical cardioid pattern.

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[10] In fact the penultimate member of that line of descent, which ended with the Sekonic L-398A (still sold as of this writing, in 2022).

Appendix D
The conundrum of the two values of C

D.1 INTRODUCTION

D.1.1 Two kinds of meters

International standard ISO 2720-1794, which in effect prescribes the behavior of exposure meters,[11] recognizes two classes of meter, the "cardioid directivity" type and the "cosine directivity" type. Both directivity patterns are defined by the standard, to a precision of about 1/6 stop.

We might think that for the cosine-directivity type, there would be no need to deal with a value of C, since these meters are not preferably used to develop an exposure recommendation.

But sometimes meters intended for reflected light metering are equipped with cosine-directivity sensors.

In any case, ISO 2720 provides (separate) ranges of C for both types of meter. The values of the range for the cardioid-directivity meter are essentially 4/3 the values of the range for the cosine-directivity meter.

D.1.2 The conundrum

What does this mean? We might think that the exposure equation is expected to be based on the illuminance, *E*, as created by a single beam of light arriving along the axis of the dome or perpendicular to the plane of the disk. Certainly for that situation, we would think that both types of meter should deliver the same exposure recommendation.[12]

So there is a conundrum here.

D.2 MY SUSPICION

D.2.1 Introduction

I suspect the solution to this conundrum is as follows.

D.2.2 The standard exposure equation

International standard ISO 2720-1074 defines how the behavior of exposure meters, of both reflected light and incident light varieties, is

[11] The title of the specification weasel-words that, saying that the document is a "Guide to product specification"

[12] In fact, the procedures intimated by the standard for testing the calibration of a meter are predicated on such a "head on" test light beam.

quantified. It presents, albeit in a different form, what I call the *standard exposure metering equation for incident light metering*:

$$\frac{t}{N^2} = \frac{C}{E\,S} \qquad (5)$$

where t is the exposure time to be used (in seconds), N is the f-number of the aperture to be used, E is the measured illuminance upon the scene (in lux[13]), S is the sensitivity of the film or digital imager (as an ISO speed number), and C is the incident light metering constant (a parameter of the specific meter).

The quantity t/N^2 can be thought of as quantifying the recommended photographic exposure, a combination of exposure time ("shutter speed") and aperture ("f-number"). We note that greater values represent greater exposure settings (from a greater exposure time and/or a lesser f-number, and thus a larger aperture).

We can unclutter the equation a bit by using the symbol P for the recommended photographic exposure, thus:

$$P = \frac{C}{E\,S} \qquad (6)$$

We note that if (while C and S remain unchanged) we increase E, the measured scene luminance, the exposure recommendation must decrease (a fact of course well recognized in photography).

Finally we note that (with S unchanged) to maintain a given value of P when we lower the value of C, we must have a lower value of E as well. We can look at this situation, in which the meter gives the same response (a value of P) for a lower value of E, as an increase in the "sensitivity" (to light) of the meter. Thus we can say that an decrease in the value of C represents an increase in the *sensitivity* of the meter.

D.2.3 About C

The standard does not prescribe a specific value of C, but rather states a range of allowable values. This recognizes the fact that there is no unique value of exposure for a certain scene that is "ideal". In reality, a manufacturer may choose for his exposure meter a value of C that he feels will in the most cases for the most users give an exposure result that the user will consider "right".[14]

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[13] Or. alternatively, in footcandles, but if so then C will have a different value from when E is denominated in lux.

[14] The standard nobly describes the selection of a value of C or K by statistical analysis of the observations of a large number of observers as to the "acceptability"

But the standard prescribes two different allowable ranges of C, one applicable to meters with a cardioid directivity pattern and one for meters with a cosine directivity pattern. The range for cardioid pattern meters is essentially 4/3 as great as the range for cosine pattern meters.

What's with that? This is the conundrum I address here.

D.2.4 Which E is that?

We know from the definition in the standard about testing for the value of C that the this value is defined in terms of the meter's exposure recommendation output for a given incident illuminance **when that illuminance is from a quasi-point source**; that is, for illumination arriving from a single direction (presumably aligned with the "axis" of the meter), "head-on" illumination.

So an inference as to the calibration of a meter in terms of its rated value of C pertains to the "head-on" sensitivity.

But I suspect it is also assumed that in actual use, the illumination is uniformly omnidirectional (as is, for example, approximated in a typical midday outdoor setting). And the prescribed values of C (a range) are presumably chosen so as to produce a "desirable" exposure result in this realistic lighting situation (not in the situation, used for calibration testing, where the only light source is exactly "head-on").

D.3 AN EXAMPLE

D.3.1 Introduction

Now, suppose just by way of example, a manufacturer of a "dual mode" meter chose to use a C of 400 for the cardioid mode and a C of 300 for the cosine mode (following the ratio between the ranges of the two values given by the standard).

That means that the "head on" sensitivity of the meter in the cosine mode would have to be 4/3 times the sensitivity of the meter in the cardioid mode (the implied sensitivity varying as the inverse of C, as we saw earlier).

But, regardless of the mode of the meter (maybe there **is** no meter), for a given illuminance field we would wish to use the same exposure settings for the actual "shot". Thus we would want either mode of the meter, for a subject in a given uniformly omnidirectional illuminance field, with the corresponding value of C for that mode in effect, to recommend the same exposure settings. Will that actually work out?

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to them of sample images taken with various exposures over a range of subjects illumination conditions. And that may in fact be what the manufacturers do.

D.3.2 Assumed directivity patterns

Before I proceed, we will need to assume a specific directivity function for both modes of the meter. For the cosine mode, I will assume that in fact the directivity pattern is the theoretical one.

Recall that this pattern is zero beyond 90°, since for light arriving from such an angle, it would strike the back of the receptor/sensor.

As to the cardioid pattern, we know that the theoretical pattern would not likely be achieved, owing to progressive shading of the receptor by the meter body as we pass 90°.

As a quick and dirty recognition of this decline from the theoretical cardioid directivity function beyond 90°, I will just assume that the pattern is the theoretical one up through an angle of 105°, and then drops off to zero[15] [16].

D.3.3 The overall response of the meter

For the real meter, what the meter considers to be *E* is the sum of the influence of the light striking the meter's receptor from all directions, the impact of a ray from any certain direction being weighted by the meter's directivity in that direction.

In our numerical model, we do that by integrating, over the appropriate range of angles, the product of (a) a constant (representing the uniform illumination field), (b) the value of the meter's directivity for that angle, and (c) the inverse of the assumed value of C (the assumed relative overall sensitivity of the meter). I actually do that by discrete summation in steps of 1°.

I do that for the theoretical cardioid pattern (over a range of 0-105°) and the theoretical cosine pattern (over a range of 0-90°).

The two results are essentially equal.

Thus, in both modes, for our assumed uniform omnidirectional illumination field, the meter would give essentially the same exposure recommendation, a requirement I postulated earlier.

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[15] Why that particular limit? Because it makes the answer come out just right. (Hey—that sort of thing worked for Norwood!)

[16] In effect, I assume that this would have the same results as the pattern assumed for "actual use" by the wonks who wrote the standard, who of course don't tell us anything about this.

This only works out when we have different values of C for the cardioid and cosine directivity modes, and in fact only if those two values of C have the ratio essentially implied by the standard.

D.3.4 Conclusion

The above demonstration (subject to my many assumptions) bolsters the credibility of my conjecture about the reason for the two values of C.

D.4 IN PRACTICE

D.4.1 "Norwood Director" style meters

I note that in all of the manuals I have for "Norwood Director" style meters, made by a succession of manufacturers, there is no discussion of using the meter with the "disk" receptor for the determination of photographic exposure. In all those manuals, only in the one for the Sekonic L-398A are separate values of the C of the meter for the hemisphere and disk receptor modes. But again, in that manual, there is no discussion of using the meter with the "disk" receptor for the determination of photographic exposure. So the second value of C is not of any consequence.

D.4.2 The Sekonic L-408 meter

This is a digital exposure meter, with both incident light and reflected light metering modes.

The receptor for the incident light mode is a hemisphere, but by depressing it, it becomes part of a receptor system that essentially has a cosine response (and thus is suitable for the measurement of illuminance). It is then equivalent to a disk receptor.

In the manual for this meter, the use of the matter in this "disk-like" configuration is only discussed in connection with the determination of balance between separate photographic light sources, and for the measurement of illuminance in other than a photographic exposure determination scenario, never in the context of photographic exposure determination.

In neither of those situations is the matter of the incident light metering calibration constant, C, pertinent. Nonetheless, the manual states separate values of C for the hemisphere receptor and disk receptor configurations.

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Appendix E
Measuring illuminance and the "footcandle" scale

E.1 PREFACE

This matter does not directly relate to the matter of Norwood's dome, and perhaps would be more properly a part of the article on the Norwood Director family of exposure meters. But the discussion depends on other matters discussed at length in this article, so here it is.

E.2 BASIC METER OPERATION

In all the exposure meters of the "Norwood Director" design, the meter movement itself gives its indication on a scale marked in terms of illuminance, always in the unit *footcandle*. The user then enters that indication into the exposure calculator (a form of circular slide rule) by turning the input dial of the calculator until a pointer is at the meter movement indication.

The scale of that calculator dial, also denominated in footcandles, is logarithmic, just like the basic scales on the classical linear slide rule. That is, successive equally-spaced scale marks might be 40, 80, 160, 320, etc.

The user has also set the film speed on another input dial.

Now, two adjacent concentric scales, one marked in exposure time (shutter speed) and the other in aperture (as an F-number), present the output of the calculator, the *exposure recommendation*, as a continuum of equivalent combinations of those two attributes.

E.3 THE CALCULATOR AND THE STANDARD EXPOSURE METERING EQUATION

It might seem that the calculator should work the standard exposure metering equation, which is:

$$\frac{t}{N^2} = \frac{C}{E\,S} \qquad (7)$$

where t is the exposure time to be used (in seconds), N is the f-number of the aperture to be used, E is the illuminance on the scene, S is the sensitivity of the film or digital imager (as an ISO speed), and C is the incident light metering constant (a fixed parameter of the meter).

Note that t/N^2 is what I call the *photographic exposure*, and larger values represent greater photographic exposure.

E.4 TWO VALUES OF C

E.4.1 Introduction

But we learned in Appendix D why it is appropriate for a meter to have different values of C for exposure metering with a disk (cosine pattern) receptor and with a dome (cardioid pattern) receptor. How do we accommodate that? There are three well-known ways.

E.4.2 Two arrows for the input dial

A direct solution is that, for the "input" dial of the calculator, there are two arrows against which the meter movement indication is set, one to be used with the disk receptor is in use and one when the dome receptor is in use. If the meter movement indication in both cases is the actual observed illuminance, then these are separated by the distance corresponding to the ratio between the two values of C.

In any case, this implementation is not used in any of the Norwood Director family of meters.

E.4.3 Different photometric transfer coefficients

A second solution involves what I call the *photometric transfer coefficient* of the two receptors themselves. This quantity is the ratio of the average illuminance upon the sensor proper to the illuminance upon the receptor (in the case of the dome receptor, this would be for a test illuminance arriving along the axis of the dome).

If the ratio of this property for the two receptors is the ratio of the two values of C adopted for the meter, then this story can work out properly.

Note, however, that this means that if, with one of the receptors in place, the indication of the meter movement is in fact the actual illuminance upon the receptor, with the other receptor in place, the indication cannot be the actual illuminance upon the receptor. In the latter case, that indication is just an arbitrary way of transferring the meter movement indication into the calculator. (Or perhaps in both cases.)

This is not any problem when actually doing exposure metering. In that context, in fact, the meter movement indication (albeit in illuminance units) is just an arbitrary way of transferring the meter movement indication into the calculator.

Where there might be a problem is when using the meter not for exposure determination but rather in just measuring actual illuminance for some other purpose.

But in fact the measurement of actual illumination calls for a meter with a cosine response. Thus, for that work, we must put the disk receptor in place.

And so we might reasonably assume that the design of all this is such that with the disk receptor in place, the meter movement indication, in footcandles, is in fact the observed illuminance.

Then, when doing actual photographic metering with the dome receptor in place (recommended for must such tasks), the meter movement indication becomes just an arbitrary way of transferring the indication into the calculator. And why not? In that work, we do not treat the indication of the meter movement as a "result".

This is the approach seemingly used on the meters of interest here.

What a lovely story. But as we will see shortly, it just doesn't always happen that way.

E.4.4 A hybrid approach

It could well be that in designing a meter, for a tidy design of the two receptors we would end up with their having different photometric transfer coefficients, but not separated by a ratio that was the same as the ratio of the stated values of C for the two receptors.

In that case, we can again use "two arrows" for the input dial, now separated by the proper value to take account of both the ratio of the stated values of C and the ratio of the photometric transfer coefficients of the two receptors.

I will not discuss the various ramifications of this approach.

This is not done on any of the meters of interest.

E.5 RECOMMENDATION TO THE READER

Much of the work in this appendix depends on concepts, terms and symbols introduced in Appendix D. If the reader has not yet read that appendix I suggest it be read now.

E.6 TYPICAL STATED VALUES OF C

The documentation for the Sekonic L-398A, the most recent (and presumably last) of the Norwood Director family of exposure meters, says that for the meter in the hemisphere mode the value of C is 340; for the disk mode, the value of C is 250.

E.7 THE "CALCULATOR C"

Without doing any photometric testing, we can learn a bit about the realities of an actual meter by "reverse engineering" its calculator.

We set arbitrary values of S and E, and note a resulting pair of t and N values. We then plug all those values into this form of the standard exposure metering equation:

$$C = \frac{t\,E\,S}{N^2} \qquad (8)$$

This value of *C* is what I call the *calculator C*. If in fact the value of *E* (the meter movement indication) is the actual illuminance, then the behavior of the meter follows the standard exposure metering equation in accordance with that value of C.

Suppose the *calculator C* is in fact the stated C for the disk mode. Then if in fact the meter movement indication, *M*, is the actual illuminance, the meter with the disk in place will indeed behave as per the stated value of C.

In that case, with the dome in place (for which the stated C in this example is a different value), for the meter to behave as dictated by that value of C will require the meter movement to indicate an illuminance **not** the actual illuminance upon the receptor.

But we have already ascertained that this is OK. The only task for which we take the meter movement indication as the "meter reading" is the measurement of luminance (not an exposure measurement). That is properly done with the disk in place, and in the above story in that mode the meter movement indication must be the actual illuminance.

E.8 BUT IN REALITY

So is that story actually fulfilled by the exposure meters of interest here? No. We see a specific example of this for the Sekonic L-398A, the last of the "Norwood director" style analog exposure meters, in Appendix F

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Appendix F
Photometric evaluation of specimen Sekonic L-398A meter

F.1 DEFINITION OF TERMS AND QUANTITIES

F.1.1 Meter movement indication

I use the term meter movement indication, *M*, for the value shown by the meter needle, which in the meter of interest is denominated in footcandles.

F.1.2 Calculator input

The input dial of the calculator is, in usual exposure metering operation, set to the value of the meter movement indication, *M*. Accordingly, I use the symbol *M′* for the input dial setting.

F.1.3 Calculator C

F.1.3.1 *Definition*

I use the term *calculator C* (C_C) for the value of C that a meter would exhibit if the calculator input, *M′*, were in fact precisely the actual observed illuminance, *E*.

It is in any case defined by:

$$C_c = \frac{t\,M's}{N^2} \qquad (9)$$

F.1.3.2 *Determination*

We determine C_C by inspection of the calculator, setting *M′* and *S* to handy values and noting a matching pair of *t* and *N* values, and then using equation 9 to get C_C.

F.1.3.3 *Shortcut to C*

Having determined the value of C_C for a meter's calculator, then in photometric testing we can determine the actual value of C for the different receptor modes merely by noting the meter movement indication, M_T, and the test illuminance causing it, E_T, and then using this equation:

$$C = C_C \frac{E_T}{M_T} \qquad (10)$$

This saves the tedium of, for each test, determining a value of *M*, setting the calculator, and then reading T and N precisely, and then calculating the attained value of C.

F.1.4 Exposure recommendation

In normal use, the output of the meter we use is an exposure recommendation (PER), a recommended set of equivalent combinations of the exposure time (shutter speed), t, and the aperture as an f-number, N, for which I use the symbol P. It is of course defined thus:

$$P = \frac{t}{N^2} \qquad (11)$$

My term "recommended" is to remind us that (a) the photographer may or may not set the camera that way and (b) there is no "correct" exposure, nor exposure result.

F.2 SCALES

The scales on the exposure calculator are all logarithmic (just like the basic scales on a conventional linear slide rule). The markings on the meter movement scale are logarithmic.

F.3 CAVEAT

The light source used for the photometric testing was not ideal, and did not match the specification in the standard.

The illuminometer used to determine illuminance of the test illumination does not have its calibration traceable to any standard.

The scales on the meter for t and N are only marked in one-stop increments. They can be credibly read to a precision of 1/4 stop, and, with a little imagination, to 1/10 stop. The scales for M and M' are marked at 1/2 stop points, but the practical resolution is (again with a little imagination) to 1/10 stop.

As a result of all this, we should not consider the numerical results reported here to be precise. Neither should we be surprised that two sets of photometric tests, made with different light levels, led to significantly differing results as to the meter properties. We should not conclude from this that the properties being investigated vary with light level, just that two tests each had considerable uncertainty.

F.4 STATED VALUES OF C

The manufacturer of the meter, in the "specifications" section of the official manual, gives the value of C for the cardioid (dome) mode as 340, for the cosine (disk) mode, 250. The ratio between these is 1.36, quite near the 1.33 intimated (but not prescribed) by the standard.

F.5 OBSERVATION AND MEASUREMENT RESULTS

F.5.1 Calculator C

The calculator C was determined, based on careful observations of the calculator, to be approximately 318.

If we consider equation 10, we see that, if the meter movement indication, M, is to actually show the observed luminance, E (as we feel is vital in the disk mode if we are to use the meter to measure actual luminance), then the actual value of C (in the disk mode) must be the same as the calculator C.

But we have just observed that, in this meter model, the calculator C is about 315, whereas the manufacturer states the C for the disk mode as 250. So, even before we have made any photometric measurements, we are off on a bad foot.

F.5.2 Photometric measurements

F.5.2.1 *Conditions*

Two sets of measurements were made on the specimen L-398A meter. In each the meter was exposed "head on", to a light beam whose luminous flux density was measured at the meter site with an illuminometer.

In each case, measurements were taken of the meter movement indication with both types of receptor in place. The receptors were the ones furnished with the meter as we received it.

F.5.2.2 *Results*

The raw results of the photometric tests are given in this table, which also continues to give the values of *C* implied by the data:

Test illum.	Dome receptor			Disk receptor		
	Met. mvt. ind.			Met. mvt. ind.		
lux	ft-cd	lux	C	ft-cd	lux	C
900	98.5	1060	270	80	861	332
1155	121	1302	282	113	1216	302

Perhaps the most startling result is that, for both tests, the C in the dome receptor mode is less than that in the disk mode. Based on the rationale described in Appendix D and its extensions, we would have expected the C in the dome mode to be **greater** than that for the disk mode.

In any case, for neither mode is the exhibited value of C very close to the stated value. That is summarized by this table:

Test illum.	Dome receptor				Disk receptor			
	Value of C		Error		Value of C		Error	
lux	Stated	Actual	%	stops	Stated	Actual	%	stops
900	340	270	-19.1	-0.33	250	332	+32.8	+0.41
1155	340	282	-15.3	-0.21	250	302	+20.8	+0.27

Note that an actual value of C that is lower than that intended results in a photographic exposure recommendation (PER), *P*, that is lower than that intended.[17]

Most often, it is the dome receptor mode that would be used for actual exposure metering. There we see that the meter could be expected to recommend an exposure about 1/4 stop lower than intended. That is, however, not "substantial" in photographic terms.

In special cases where the disk mode is used for actual exposure metering, we can expect a PER of about 1/3 stop higher than intended. That is, however, still not really "substantial" in photographic terms.

A separate issue is that of when we use a meter of this type to actually measure actual illuminance (as to measure the illuminance on a work table). In that case, the meter movement indication is the result we take from the meter. No photographic concepts are involved, and the exposure calculator is not involved.

Only the disk receptor mode is really of concern here, as that mode is needed to measure actual illuminance.

Based on our testing, the implications on this usage are shown in this table:

Test illum.	Disk receptor		
	Meter mvt. ind.		Error
lux	ft-cd	lux	%
900	80	861	-4.3
1155	113	1216	+5.3

The substantial difference between our two tests makes it hard to conclude what error in this type of work might be expected. Still. for this type of task, an error of the magnitude seen here is not usually problematic.

F.6 CONCLUSION

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[17] We must be mindful that such a PER is not "incorrect", given that there is no "correct" exposure nor exposure result.

There are certainly a few oddities noted during the photometric testing and related analysis of the Sekonic L-398A exposure meter. But, at the end of the day (if our specimen is typical of the model), It looks as if the meter performance for exposure determination should lead to exposure recommendations close to those we would expect to get from a meter with the values of C stated in this meter's specifications. (I have to say it that way since there is no such thing as a "correct" exposure recommendation.)

As to the use of the meter (with the disk receptor in place) to measure actual illumination, there again the error observed in our testing is not so great that it would probably be problematic in typical uses of this type.

Again I caution the reader that the photometric testing done here was not "highly reliable", and so the results above might not be as accurate as we might wish.

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