90th birthday series

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

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Summary

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 multi-source lighting setups, especially those of interest in cinematography and portrait photography.

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

But it is not at all obvious, even after considerable study, just how and why meters following Norwood's principle give this long-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 ("reflected light" metering) or the illuminance of the illumination on the scene ("incident light" metering), and from that (along with the known or assumed sensitivity of the film or digital imaging system in use) provides us with a *photographic exposure recommendation* (PER). 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 distribution of photometric impact on the film or digital 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 usual 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", and stuff we know to be "black" will look "black".

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 face shot of 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). If we perfectly attain objective C, the result will be as seen in Figure 1.

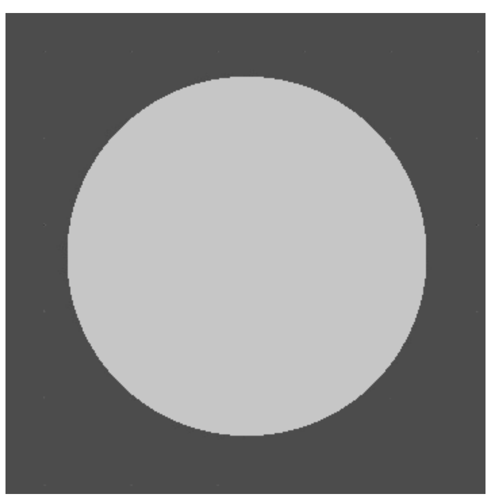

Figure 1. Sphere under uniform omnidirectional illumination

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 rather wish a photo of a sphere to look like one of the images in Figure 2.

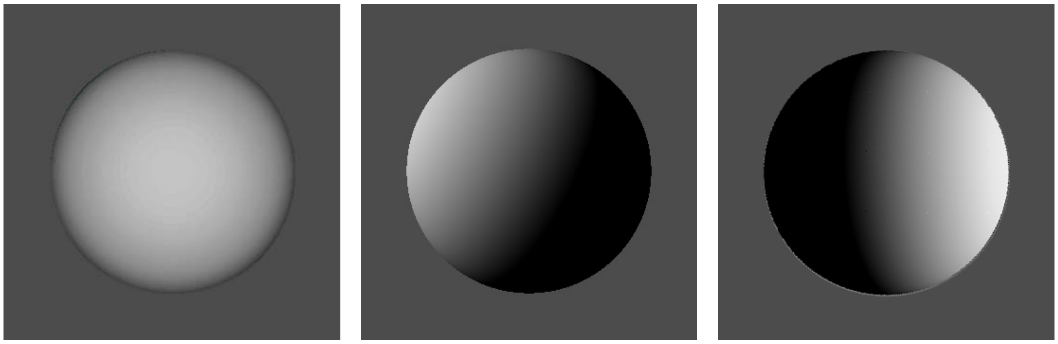

Figure 2 a, b, c. Sphere photographed under various illumination setups

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.

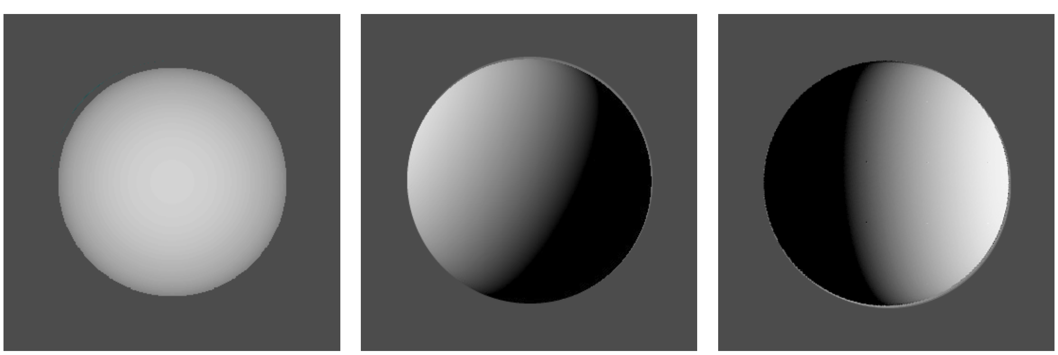

Figure 3 a, b, c. With a greater exposure

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 often want to use a more sophisticated lighting technique that will "sculpt" the features of the subject.

In typical practice, under the so-called "key-fill" technique, the subject of the shot is illuminated by two light sources. 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 of the subject. With the lighting technique I mention above, the left cheek of our subject (on our right) 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.

I do note that in the sample image of Figure 4, essentially all areas of the models face and torso fall within the luminance range of the digital representation; that is, no area went "to saturation" nor "to full black".

1.7 Duplex metering

1.7.1 *General*

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[5] is used to take separate readings while its receptor faces the two principal light sources. The average of the two meter readings (on an illuminance basis) 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? Not that I know of.

1.7.2 *An important special case*

It is interesting to consider the result of this process in the case where the only lighting is a "key" light directly to the side (that is, whose position is 90° to the side)—there is no "fill" light.

I will spare the reader the entire train of thought, but the bottom line is that in this case, using duplex metering, the meter would call for twice the exposure that would have been called for if the light source had been "head on" ("one stop" greater). In terms of meter behavior, this means that the meter's directivity at an angle of 90° is 0.5.

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[5] Ideally, this ,meter should read the true illuminance on a plane perpendicular to "head-on of the mater". That would imply that the directivity function of the meter's receptor would be a cosine function.

1.8 A rule of thumb

A "rule of thumb" widely suggested at one time, was, when the light source was directly to the aide, to use a photographic exposure one stop greater (twice as great, numerically) than if that same light source had been used "head on".

This is precisely consistent with the result of duplex metering for that same lighting situation (as discussed in Section 1.7.2). A further part of the rule of thumb says that for the light "to the rear" of the subject (typically at an angle of 135°) the exposure should be increased by a further one stop (2 stops greater than with the light "head on")

But, more recently, it has been suggested that the exposure for the "side lit" situation should be 1/2 stop, or maybe 2/3 stop, of that with the same lighting "head-on" (and that for a "to the rear" location the exposure be greater than for "to the side" lighting by that same amount).

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 collector" [my term] (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, starting in 1947, under Norwood's patent, by Photo Research Corporation (founded in 1941, perhaps at Norwood's urging, by Norwood's colleague, cinematographer Karl Freund). 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.

Figure 6. Karl Freund (center) in 1941

Image: International Encyclopedia
of Cinematographers

In fact, in Figure 6 we see (in 1941) Freund (with Risë Stevens and Nelson Eddy, on the set of "The Chocolate Soldier"), using what we believe to have been an early prototype of this new meter. (We note the use of "key-fill lighting in this photo!)

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

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.

A short while later, a second manufacturer was also licensed under Norwood's patent, and developed the meter we see in Figure 7 (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 7. 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.

Figure 8. Sekonic Model L-408 exposure meter

Photo by Kyu Hachi

We see a typical modern such meter, this one digital, in Figure 8.

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 9.

Figure 9. 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 HOW DOES THIS WORK?

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 Little 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.)

3.3 Norwood's original vision

3.3.1 *The points*

Norwood's original vision was that (and I paraphrase a lot):

a. The best photographic exposure of a human face should be determined based on the average illuminance on the part of the face visible to the camera (presumably following the same exposure equation used for "head-on illumination").

b. A meter's hemispherical light receptor, facing the camera, is a good proxy for the part of a human face visible to the camera.

c. A meter with a hemispherical receptor would respond to the average illuminance on that hemisphere.

d. Therefore, a measurement made with an exposure meter with a hemispherical receptor, calibrated to produce a "desirable" photographic exposure recommendation for "head-on" illumination, should produce an equally "desirable" photographic exposure recommendation for other lighting setups.

3.3.2 *Commentary*

Point (a): This is intuitively credible, but there is no satisfying theoretical model to support that assertion. Problematical is that with the light source to the side, the subject's features are intentionally shadowed, and it is not clear what effect that has on a viewer's assessment of the overall exposure result.

Nonetheless, this "rule" can be considered consistent with the actual results expected to be attained with duplex metering (or even the "rule of thumb"), for the key light at an angle of 90° (an important "special case"). And it is essentially consistent with the findings of Norwood's subjective testing (as described in Section 3.5 and more thoroughly in Appendix A

Point (b): This is reasonable.

Point (c): This is essentially true.

So Norwood's "vision" was apt, maybe.

3.4 Some elaboration

In a paper by Norwood published before the Society of Motion Picture Engineers in 1941[6], Norwood suggests that, based upon photographers' experience with metering of key-fill lighting situations, light directed on a subject's face from an angle of 90° to the side of the camera was only "half as effective" as light directed from the camera position. (This is consistent with the "rule of thumb" described in Section 1.8). What this suggests is that for light coming from an

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[6] "Negative Exposure Control", *J SMPE 1941, 36:389-402*

angle of 90°, the "proper" photographic exposure would be twice what it would be for that same light directed "head on" to the subject.

He then goes on to say that for an exposure meter with a hemispherical receptor, with the apex of the hemisphere facing the camera, the sensitivity of the meter to light arriving from an angle of 90° to either side would be half its sensitivity to light coming from "head on". Thus such a meter could be used directly to determine the optimal photographic exposure for such a lighting setup.

It is in fact true theoretically that the response of a hemispherical receptor meter to light arriving at 90° to "head on" is half its response to the same light arriving "head-on".

This rationale is more restricted than Norwood's original "vision". It only deals with a specific "not head-on" lighting setup.

3.5 Something more "scientific"

In 1950, perhaps in response to continuing pressure from the community for a "scientific" explanation of his principle, Don Norwood published a paper before the Society of Motion Picture and Television Engineers [7] (the new name of the same society) that gave a helpful outlook into that mystery, not on the basis of a theoretical model but rather through analysis of subjective observations in an empirical 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).

The data from these tests suggested that typically the required increase in exposure was inversely proportional to the angle from which the light arrives.

Then, if an exposure meter were to recognize this, its *directivity curve* (the plot of its response to some arriving light beam, as a function of the angle at which the light arrives at the meter, reckoned from

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[7] "Light Measurement for Exposure Control", *J SMPTE 1950, 54:585-602*.

"head" on, would be proportional to the inverse of the angle. If we plot that in polar coordinates, the curve is what is called an *Archimedean spiral*.

Notion then said that, happily, this was essentially the theoretical directivity curve of a meter with a hemispherical light collector.

Less happily, that is not the theoretical directivity curve of a meter with a hemispherical collector. Rather that curve is what is called a *cardioid*.

But, happily after all, those two corves are not much different. And remember that this whole metering process is rather arbitrary anyway.

So it seemingly turns out that a meter with a hemispherical light collector in fact does a good job of giving us a good photographic exposure recommendation.

In a way, the results of these tests vindicated Norwood's original "visions" of an improved incident light exposure meter.

Was Norwood prescient? Or just lucky? I leave that to the reader to decide.

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 (as discussed on Section 1.7) Seemingly, there was general satisfaction with this technique, other than that it was rather time-consuming.

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 be expected to yield approximately the same exposure recommendation?"

Yes. Table 1 gives the results of a numerical 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). The assumed key:fill ratio is 8:1 (as in Norwood's paper).

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.

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

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 collector 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.

6 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 that implies as an optimal photographic exposure setting). After all, the meter has most of the necessary ingredients to do that. Three common such situations are:

- In some photographic situations, it is considered 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.

- If for some reason we wish to use the "duplex" metering technique, it is generally suggested that for this a meter that measures actual illuminance is preferred.

- When we wish to determine the ratio between two photographic light sources, which is said to be best done in terms of the actual illuminance 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 that use by having an alternate light collector (the "front end" of the receptor system), this one generally in the form of a disk, which can be put in place by the user instead of the dome collector to give the meter a cosine directivity..

In Figure 10 we see both the collectors on a Sekonic L398A meter, the dome on the left, the disk on the right..

Figure 10 a,b. Sekonic L-398A with dome and disk collectors

In other exposure meters (such as many of the Sekonic digital exposure meters, including the one seen in Figure 8), the dome can be pushed down to play a role in a complicated structure that essentially gives a cosine response.

There are. however, some discrepancies in this mode of use, which are beyond the scope pf this article.

7 A LATER REFINEMENT

Norwood, in a 1961 patent, calls attention to the "rule of thumb" I discuss in Section 1.8, but goes on to say that, because (in part) of changes in "what lighting effects are [now considered] aesthetically most desirable [by photographers]", it was at that time often considered than light coming from the side (90°) should be "discounted" not by one stop but rather by only 1/2 stop (or maybe 2/3 stop).

Following that, Norwood described changes in the light collector from its original hemispherical form to a modified form that would gave a directivity curve consistent with such a new "rule of thumb" at the 90° angle.

He suggests specifically that this ideally be implemented to give a relative directivity at 90° of -2/3 stop (0.63 times the "head on" sensitivity).

8 BROADER APPLICABILITY

Norwood's original work related primarily to closeup cinematography and the parallel field of portrait photography, and this article essentially hews to that context.

It is said by certain incident light exposure meter manufacturers that the use of the dome collector as the basic configuration of their instruments is desirable as to exposure metering in such contexts as landscape photography. I have done little thinking about, and no actual investigation of, that.

9 APPENDIXES

Additional detailed technical discussions of various matters relating to Norwood's principle are covered in the 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

10 ABOUT "90TH BIRTHDAY SERIES"

This issue of this article is one of several publications made around the time of the 90th birthday of the author, which is May 8, 2026.

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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 actual subjective observations in a test program.

The paper 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 lalidity of a "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 program itself

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 light luminous flux density ratio (at the subject) 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° were 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. I do not know the increment in exposure used between these shots, but I 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 exposure result" 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 of 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 (with "head-on" lighting) was consistently greater than the meter-indicated exposure for the reference shot by an amount that increases in a consistent way 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 column 2 entry for 45° presumably means "a little less then 1/2 stop". (To precisely 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") varies with the angle at which the key light was placed. This is shown in column 3 of the table. Norwood described this value as the *effective illumination factor* for that key light angle. We note that these data points precisely follow a linear function of angle.

He then says that if the relative response of an exposure meter, as a function of the angle from which the light arrives, follows that pattern of, 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.

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

Column 4 of Figure A2 shows that needed directivity of the meter. Again this precisely follows a linear function of angle.

The apparent underlying directivity function, plotted in polar coordinates, is a figure called as *Archimedean spiral*.

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, recommend the "best" photographic 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 caused 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 "demonstrated" the idea 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 at the subject (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 Norton found 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 part of the stimulus is not changed when we move the key light to 90°.

Accordingly, the meter 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 0.44, actually). This is of course not a great discrepancy (about 0.2 stop).

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.

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.

A.3.3 The directivity of the meter

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). He (correctly) observes that for an angle of incidence of the light of 90°, only half of the dome would be illuminated. Thus, we would expect the meter response at that angle (in illuminance terms) would be 0.50 of what it would be for the same illumination "head on" to the meter. In other words, the directivity of the meter at 90° should 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 seemingly needed.

A.3.4 No quite so

But Norton's conclusion was flawed. The theoretical durativity curve of a meter with a hemispherical receptor, if plotted in polar coordinates, is actually a geometrical figure called the *cardioid*.

For comparison, we see in Figure 11 these two functions platted in polar coordinates.

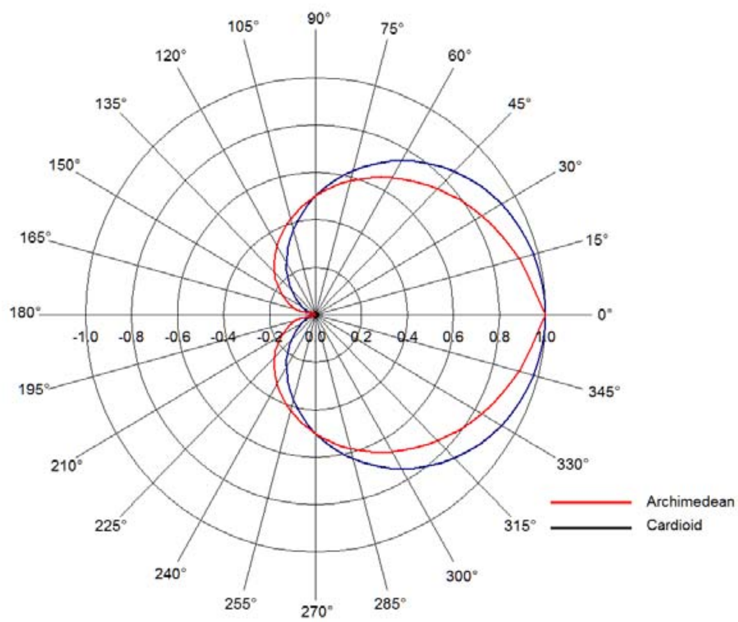

Figure 11. Archimedean spiral and cardioid directivity patterns

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) decreases inversely linear with the angle of the key light.

   Comment: I will accept that at face value. This is shown by the results of the test program.

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: Not so. Such a meter will actually theoretically exhibit a directivity that, if plotted in polar coordinates, is a *cardioid*.

A.4.2 An observation

The results of the test Norwood reported in this paper essentially vindicated the point of his original "vision" which I prraphrase as Point a in Section 3.3.1.

A.4.3 Grading the paper

The lapses from rigor and inconsistencies 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 serious 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, but lucky as to his result? I leave it to the reader to contemplate that.

A.4.4 The good news

Norwood's paper is an empirical 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".

The actual lapses in Norwood's presentation appear to 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 recommended by these meters very often lead to an exposure result that the photographer or cinematographer deems "good".

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Appendix B
Derivation of the cardioid directivity of the hemispherical dome

B.1 THE DIRECTIVITY RESPONSE OF THE HEMISPHERICAL RECEPTOR

Of interest is the "directivity pattern" of a hemispherical incident light metering sensor (implemented with a flat sensor covered by a translucent hemispherical dome "collector"). I make two assumptions (the first one actually being more of a "condition):

- The light source is sufficiently small, and at a sufficient distance, that all rays from it striking any part of the collector will come from the same direction (will be parallel).
- A fixed fraction of the luminous flux striking the collector at any place and at any angle will impact the actual photodetector.

That having been said, then the relative sensitivity of the meter to light arriving from any direction will be proportional to the projected area of the collector as seen from that direction.

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

I will work from Figure 12.

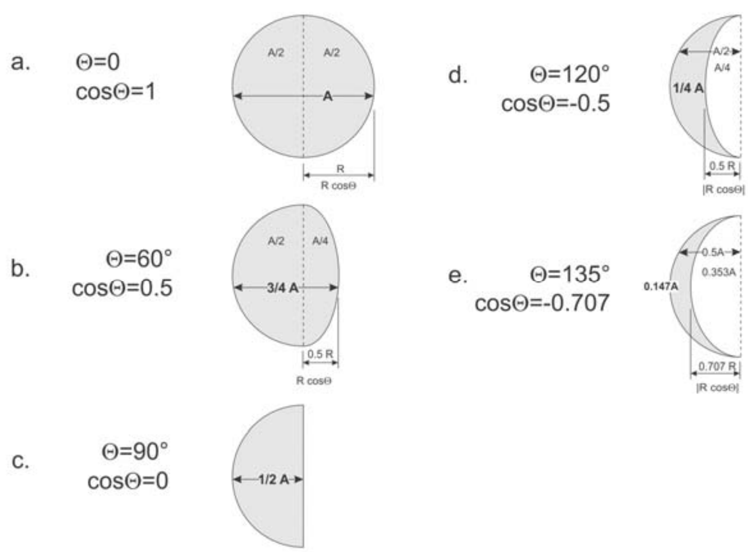

Figure 12. Projected area of the hemisphere from different viewing angles

<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 "head on" (that is, from a point on its "polar 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 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*.

<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 left boundary is still that same curve. 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 in 3-dimensional space, 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 $\cos\Theta$, to $(A/2)\cos\Theta$, or A/4. Thus the entire projected area of the hemisphere, the sum of the two sections, is 3/4 A. (That area is shown outlined in bold.)

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

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.

Accordingly, the entire projected area of the hemisphere is just 1/2 A.

<u>Panel d— observation from an angle of 120°</u>

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 1/4 A.

Panel e— observation from an angle of 135°

In panel d, our view is from 135° to the right. We note that for $\Theta = 135°$, $\cos\Theta = -0.707$.

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" further to the 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 $R \cos\Theta$).

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 perhaps 90° there would unavoidably 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 13.

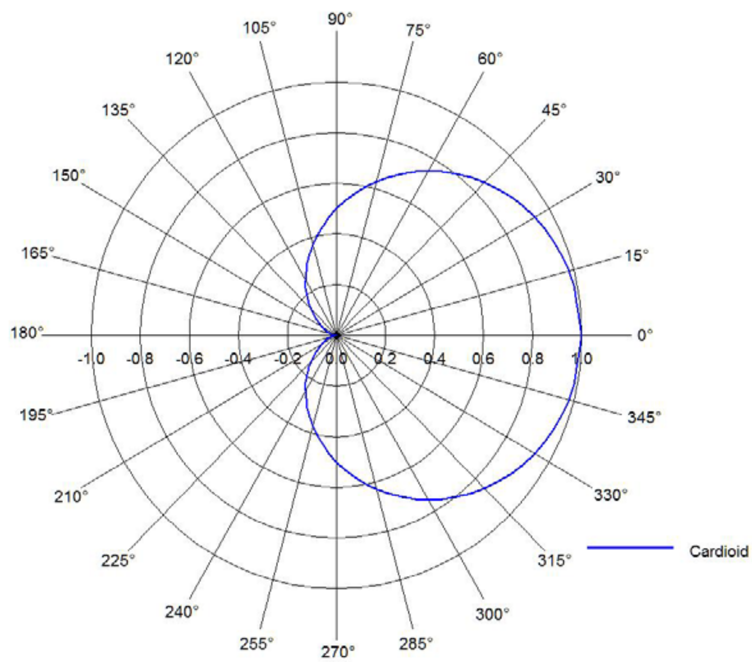

Figure 13. Cardioid directivity pattern

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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.

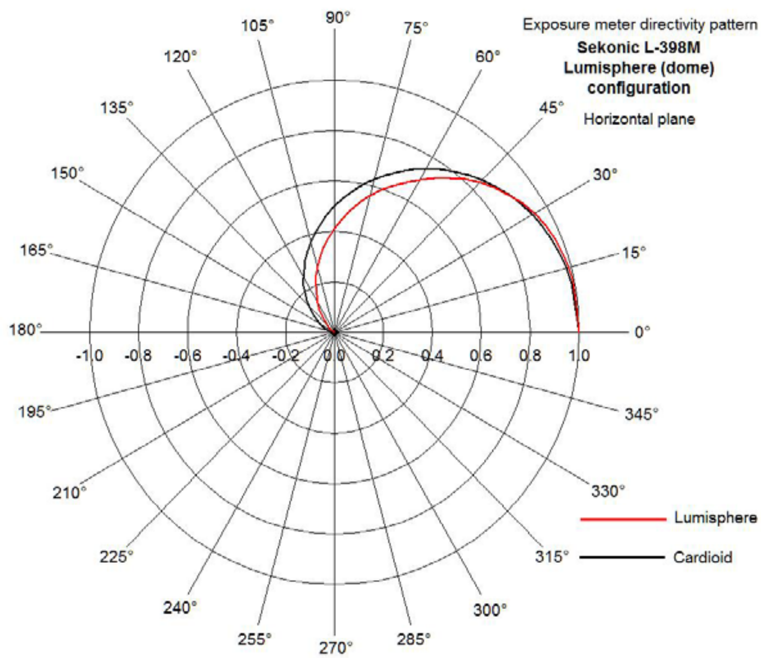

Figure 14. Sekonic L-398M–Cardioid directivity pattern

We note that the pattern exhibited by the meter 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 2026).