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Detector Response and Perfect-Lens-MTF in Polychromatic Light

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Because light sources and detectors exhibit significant spectral variations, the detector response in an optical system can generally be found only by means of a tedious numerical integration process. The evaluation of the MTF in polychromatic light requires an even more extensive numerical procedure. Here, integration results are presented for all combinations of six commonly used light sources and twelve common detectors. The MTF's for perfect lenses and efficiency factors are presented.

I. Introduction

Because light sources and detectors exhibit significant variations over the spectrum, the detector response in an optical system can generally be found only by means of a numerical integration process. This can be avoided only if the light source used is monochromatic or happens to duplicate the source used by the manufacturer to calibrate the detector; usually the designer must go through the very tedious integration process to obtain results to any degree of accuracy.[1,2]

The problem is even more serious when the modulation transfer function (MTF) of an imaging system is desired. There, the weighted average of the monochromatic MTF must be formed—a process involving such tedious numerical work that many designers will not consider it worth the trouble.

The purpose of this paper is to present integration data for a number of common light sources and detectors enabling the designer to predict easily the detector output.

The MTF of a diffraction limited lens, with circular aperture, in polychromatic light is also presented. This is of dual importance: it represents a situation met frequently and also constitutes an upper limit on the performance obtainable with any lens system. In view of the wide variety of MTF's in imperfect lens systems, it was not practical to include any of them.

II. System Efficiencies in General

In this section, efficiency factors relating output to input are formulated. This is done in general terms. The more specific formulations, given in Sec. III, together with the tables, enable the reader to apply the results to all the combinations involving six common light sources and twelve common detectors.

To facilitate formulation of these relationships in compact form, we introduce the concept of *effective spectral width* $\Delta\lambda$, which is found relative to some reference wavelength λ_0 in the spectrum. Three types of such widths will be used.

(1) The *energetic* width:

$$\Delta_e\lambda = \int e(\lambda)d\lambda; \tag{1a}$$

(2) The *luminous* width:

$$\Delta_v\lambda = \int e(\lambda)s_v(\lambda)d\lambda; \tag{1b}$$

(3) The *system* width:

$$\Delta_s\lambda = \int e(\lambda)s(\lambda)\tau'(\lambda)d\lambda. \tag{1c}$$

We also define:

(4) The *system efficacy*:

$$k_s = \Delta_s\lambda/\Delta_e\lambda,$$

this represents the effectiveness of the total radiation relative to an equal power radiated at the reference wavelength; and (5) the *visual efficacy*, the system efficacy with visual detection $k_v = \Delta_v\lambda/\Delta_e\lambda$.

Here $e(\lambda)$, $s(\lambda)$, $\tau'(\lambda)$ are the source spectral radiant emittance, the detector radiant sensitivity, and the system transmittance, respectively, all at wavelength λ and all relative to those at λ_0.* $s_v(\lambda)$ is the standard photopic visibility factor (CIE, 1931), and the integrals extend over the total spectrum.

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*Note that only *power radiated* and *output per incident power* are considered and that quantum considerations are all absorbed in $s(\lambda)$.

Table I. Spectral Characteristics of Radiation Sources and Detectors

Wavelength (μ)	Radiation sources: Blackbody 3000°K	Radiation sources: Blackbody 5000°K	Radiation sources: Standard illuminant A	Radiation sources: Standard illuminant B	Radiation sources: Phosphor P-11	Radiation sources: Phosphor P-16	Detectors: Normal observer Photopic	Detectors: Normal observer Scotopic	Detectors: Photoelectric detectors S-10	Detectors: Photoelectric detectors S-11	Detectors: Photoelectric detectors S-12	Detectors: Photoelectric detectors S-20
0.35	.0255	.4764	.0051	.0883	.0000	.2000	.0000	.0000	.5540	.6210	.0310	.6800
0.36	.0324	.5200	.0064	.0964	.0000	.5400	.0000	.0000	.6780	.7800	.0420	.7600
0.37	.0405	.5628	.0081	.1043	.0000	.8800	.0000	.0000	.7720	.8380	.0580	.8250
0.38	.0499	.6044	.0098	.1120	.0000	.9999	.0000	.0006	.8380	.8700	.0740	.8800
0.39	.0605	.6446	.0121	.1565	.0300	.9700	.0001	.0022	.8720	.8870	.0900	.9270
0.40	.0725	.6831	.0147	.2065	.0900	.8600	.0004	.0093	.9100	.9050	.1060	.9600
0.41	.0859	.7197	.0177	.2605	.2000	.6800	.0012	.0348	.9400	.9290	.1220	.9900
0.42	.1006	.7542	.0210	.3160	.3430	.4600	.0040	.0966	.9650	.9690	.1380	*****
0.43	.1166	.7864	.0247	.3655	.5900	.2600	.0116	.1998	.9840	.9910	.1540	.9950
0.44	.1340	.8163	.0287	.4040	.7600	.1350	.0230	.3281	.9960	*****	.1700	.9750
0.45	.1525	.8439	.0331	.4270	.9500	.0680	.0380	.4550	*****	.9940	.1860	.9520
0.46	.1723	.8690	.0378	.4415	.9999	.0350	.0600	.5672	.9970	.9780	.2040	.9270
0.47	.1932	.8918	.0429	.4600	.9300	.0180	.0910	.6756	.9850	.9580	.2240	.8950
0.48	.2150	.9122	.0482	.4760	.8400	.0120	.1390	.7931	.9670	.9310	.2650	.8520
0.49	.2379	.9302	.0539	.4825	.7200	.0070	.2080	.9043	.9450	.9020	.5100	.8200
0.50	.2615	.9459	.0599	.4710	.6000	.0020	.3230	.9818	.9200	.8640	.9000	.7910
0.51	.2859	.9595	.0661	.4535	.4500	.0005	.5030	.9966	.8920	.8170	.4000	.7620
0.52	.3108	.9709	.0725	.4475	.3500	.0000	.7100	.9352	.8590	.7680	.0580	.7330
0.53	.3363	.9803	.0791	.4610	.2350	.0000	.8620	.8110	.8210	.7050	.0360	.7040
0.54	.3622	.9877	.0860	.4845	.1550	.0000	.9540	.6497	.7790	.6400	.0280	.6750
0.55	.3884	.9933	.0929	.5050	.0830	.0000	.9950	.4808	.7330	.5710	.0220	.6450
0.56	.4147	.9971	.1000	.5140	.0600	.0000	.9950	.3288	.6830	.4960	.0180	.6170
0.57	.4412	.9993	.1072	.5130	.0350	.0000	.9520	.2076	.6300	.4200	.0140	.5880
0.58	.4676	*****	.1144	.5050	.0170	.0000	.8700	.1212	.5750	.3460	.0110	.5590
0.59	.4939	.9992	.1217	.4960	.0000	.0000	.7570	.0655	.5190	.2680	.0080	.5300
0.60	.5200	.9971	.1290	.4900	.0000	.0000	.6310	.0332	.4630	.1970	.0050	.5010
0.61	.5458	.9938	.1363	.4925	.0000	.0000	.5030	.0159	.4080	.1290	.0000	.4720
0.62	.5712	.9893	.1436	.4985	.0000	.0000	.3810	.0074	.3560	.0790	.0000	.4430
0.63	.5962	.9838	.1508	.5050	.0000	.0000	.2650	.0033	.3090	.0470	.0000	.4140
0.64	.6207	.9774	.1580	.5110	.0000	.0000	.1750	.0015	.2670	.0290	.0000	.3850
0.65	.6446	.9700	.1650	.5195	.0000	.0000	.1070	.0007	.2290	.0180	.0000	.3560
0.66	.6680	.9619	.1720	.5250	.0000	.0000	.0610	.0003	.1950	.0120	.0000	.3270
0.67	.6906	.9530	.1788	.5245	.0000	.0000	.0320	.0001	.1630	.0080	.0000	.2980
0.68	.7125	.9435	.1854	.5195	.0000	.0000	.0170	.0001	.1330	.0060	.0000	.2690
0.69	.7337	.9335	.1919	.5080	.0000	.0000	.0082	.0000	.1060	.0050	.0000	.2400
0.70	.7542	.9229	.1983	.4955	.0000	.0000	.0041	.0000	.0830	.0040	.0000	.2110
0.71	.7738	.9119	.2044	.4810	.0000	.0000	.0021	.0000	.0640	.0030	.0000	.1820
0.72	.7926	.9004	.2104	.4645	.0000	.0000	.0010	.0000	.0480	.0020	.0000	.1530
0.73	.8105	.8886	.2161	.4470	.0000	.0000	.0005	.0000	.0350	.0010	.0000	.1260
0.74	.8276	.8766	.2217	.4345	.0000	.0000	.0002	.0000	.0250	.0000	.0000	.1030
0.75	.8439	.8643	.2270	.4260	.0000	.0000	.0001	.0000	.0170	.0000	.0000	.0850
0.76	.8593	.8517	.2321	.4235	.0000	.0000	.0001	.0000	.0100	.0000	.0000	.0680
0.77	.8738	.8390	.2370	.4270	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0520
0.78	.8874	.8262	.2417	.4305	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0400
0.79	.9002	.8133	.2450	.4300	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0290
0.80	.9122	.8003	.2482	.4300	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0190
0.81	.9233	.7872	.2511	.4300	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0110
0.82	.9335	.7742	.2540	.4300	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0050
0.83	.9430	.7611	.2569	.4300	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
0.84	.9516	.7481	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
0.85	.9595	.7352	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
0.86	.9666	.7223	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
0.87	.9729	.7094	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
0.88	.9786	.6967	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
0.89	.9835	.6841	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
0.90	.9877	.6716	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000

* THIS VALUE IS UNITY

In general terms, the detector response or output will be given by:

$$R = \int \tau(\lambda) S(\lambda) i_\lambda(\lambda) d\lambda = i_{\lambda 0} \tau_0 S_0 \Delta_s \lambda, \qquad (2)$$

where τ is the system transmittance, S is the detector sensitivity, and i_λ is the spectral input with dimensions appropriate for the detector; e.g., for a photoelectric detector, it is the spectral flux: $\tau_0 i_\lambda \equiv \Phi_\lambda$; for a photographic emulsion, it is the spectral irradiation: $\tau_0 i_\lambda \equiv E_\lambda$; and for the visual system either of these may be used. The subscript 0 indicates the value at the reference wavelength λ_0.

The spectral input i_{λ_0} at the reference wavelength may be determined from the total input:

$$i_T = \int i_\lambda d\lambda = i_{\lambda_0} \int e d\lambda = i_{\lambda_0} \Delta_e \lambda; \qquad (3)$$

so that

$$i_{\lambda_0} = i_T / \Delta_e \lambda. \qquad (4)$$

Table I. Continued

Detectors					
Photoelectric detectors			Photographic emulsions		
CdSe	Si diode	Vidicon	Blue sensitive	Ortho chromatic	Pan chromatic
.0400	.1000	.0000	3.5500	0.7940	1.0000
.0400	.2000	.0952	2.5100	0.7940	1.0000
.0400	.2400	.2190	1.9040	0.7940	1.0000
.0400	.3000	.3048	1.5850	0.7940	1.0000
.0400	.3200	.3714	1.2590	0.8320	1.0000
.0400	.3700	.4286	1.0000	1.0000	1.0000
.0400	.4000	.4762	0.7240	1.1480	0.9552
.0400	.4200	.5429	0.5760	1.2020	0.9123
.0400	.4400	.5810	0.4790	1.2590	0.8512
.0400	.4800	.6286	0.3890	1.2590	0.7580
.0400	.5000	.6476	0.3460	1.2590	0.6920
.0400	.5200	.6857	0.3160	1.2590	0.6310
.0400	.5300	.7238	0.3160	1.2300	0.6030
.0400	.5500	.7619	0.3524	1.1750	0.5620
.0400	.5900	.8190	0.4080	1.0470	0.5500
.0400	.6000	.8571	0.5020	1.0000	0.5500
.0400	.6200	.8857	0.5380	1.1750	0.6030
.0400	.6400	.9238	0.5760	1.4800	0.7240
.0400	.6500	.9429	0.5890	1.6590	0.8912
.0400	.6800	.9810	0.5760	1.8100	0.9552
.0400	.7000	*****	0.5020	1.9500	0.9773
.0400	.7200	.9619	0.3160	2.0900	0.9552
.0500	.7300	.9238	0.1260	1.7770	0.9552
.0500	.7400	.8762	0.0450	0.8710	0.9335
.0600	.7600	.8286	0.0159	0.2000	1.0000
.0600	.8000	.7714	0.0048	0.0415	1.0960
.0700	.8000	.7143	0.0014	0.0086	1.0000
.0700	.8000	.6667	0.0004	0.0018	0.6920
.0800	.8100	.6190	0.0001	0.0004	0.4370
.0900	.8200	.5810	0.0000	0.0001	0.2690
.1000	.8300	.5524	0.0000	0.0000	0.1520
.1100	.8300	.5333	0.0000	0.0000	0.0415
.1200	.8400	.4857	0.0000	0.0000	0.0113
.1300	.8500	.4476	0.0000	0.0000	0.0031
.1400	.8600	.3905	0.0000	0.0000	0.0008
.1500	.8700	.3524	0.0000	0.0000	0.0002
.1700	.8800	.3238	0.0000	0.0000	0.0000
.5000	.8900	.2952	0.0000	0.0000	0.0000
.8600	.9000	.2762	0.0000	0.0000	0.0000
*****	.9000	.2476	0.0000	0.0000	0.0000
.8700	.9000	.2095	0.0000	0.0000	0.0000
.5500	.9000	.1619	0.0000	0.0000	0.0000
.4000	.9000	.1429	0.0000	0.0000	0.0000
.3400	.9000	.1238	0.0000	0.0000	0.0000
.3000	.9100	.1048	0.0000	0.0000	0.0000
.2500	.9100	.0952	0.0000	0.0000	0.0000
.2000	.9100	.0857	0.0000	0.0000	0.0000
.1700	.9100	.0762	0.0000	0.0000	0.0000
.1500	.9200	.0667	0.0000	0.0000	0.0000
.1300	.9200	.0571	0.0000	0.0000	0.0000
.1100	.9300	.0476	0.0000	0.0000	0.0000
.1000	.9300	.0381	0.0000	0.0000	0.0000
.0900	.9300	.0381	0.0000	0.0000	0.0000
.0800	.9400	.0000	0.0000	0.0000	0.0000
.0700	.9500	.0000	0.0000	0.0000	0.0000
.0700	.9600	.0000	0.0000	0.0000	0.0000

Wavelength (μ)	Blackbody		Photoelectric detectors	
	3000°K	5000°K	CdSe	Si diode
0.91	.9913	.6592	.0600	.9700
0.92	.9942	.6470	.0600	.9800
0.93	.9965	.6349	.0600	.9900
0.94	.9982	.6230	.0600	*****
0.95	.9993	.6112	.0600	.9900
0.96	.9999	.5996	.0600	.9800
0.97	*****	.5882	.0500	.9500
0.98	.9995	.5769	.0500	.9100
0.99	.9986	.5658	.0500	.8800
1.00	.9971	.5549	.0500	.8200
1.01	.9953	.5442	.0000	.7900
1.02	.9930	.5336	.0000	.7100
1.03	.9903	.5232	.0000	.6300
1.04	.9873	.5130	.0000	.6000
1.05	.9838	.5030	.0000	.5400
1.06	.9801	.4932	.0000	.5000
1.07	.9760	.4836	.0000	.4300
1.08	.9716	.4741	.0000	.3900
1.09	.9669	.4648	.0000	.3300
1.10	.9619	.4557	.0000	.2500
1.11	.9567	.4468	.0000	.2100
1.12	.9512	.4380	.0000	.1600
1.13	.9455	.4294	.0000	.1200
1.14	.9396	.4210	.0000	.0900
1.15	.9335	.4127	.0000	.0700
1.16	.9272	.4047	.0000	.0520
1.17	.9207	.3967	.0000	.0400
1.18	.9141	.3890	.0000	.0000
1.19	.9073	.3814	.0000	.0000
1.20	.9004	.3740	.0000	.0000
1.21	.8934	.3667	.0000	.0000
1.22	.8863	.3595	.0000	.0000
1.23	.8790	.3526	.0000	.0000
1.24	.8717	.3457	.0000	.0000
1.25	.8643	.3390	.0000	.0000
1.26	.8568	.3324	.0000	.0000
1.27	.8492	.3261	.0000	.0000
1.28	.8416	.3198	.0000	.0000
1.29	.8339	.3136	.0000	.0000
1.30	.8262	.3076	.0000	.0000

On substituting Eq. (4) into Eq. (2) we obtain the response in terms of the total input:

$$R = i_T S_0 \tau_0 \Delta_s\lambda / \Delta_e\lambda, = i_T S_0 \tau_0 k_s, \qquad (5)$$

where i_T is the total *radiant* flux or irradiation at the detector, as calculated by the usual procedures (Ref. 3, Sec. 9.5.2).

Frequently the input is known in terms of *luminous* quantities i_{vT}. In those cases, Eq. (3) becomes

$$i_{vT} = K i_{\lambda_0} \int e s_v d\lambda = K i_{\lambda_0} \Delta_v \lambda, \qquad (3a)$$

and, hence,

$$i_{\lambda_0} = i_{vT} / K \Delta_v \lambda, \qquad (4a)$$

where $K = 680$ lm/W is the sensitivity of the CIE standard observer at the reference wavelength ($0.555\ \mu$) and is occasionally referred to as "the mechanical equivalent of light." Thus, Eq. (5) becomes

$$R = i_{vT} S_0 \tau_0 \Delta_s \lambda / K \Delta_v \lambda = i_{vT} S_0 \tau_0 k_s / k_v. \qquad (5a)$$

III. Specific System Efficiencies

By applying Eq. (5) to the specific detectors, the following results are readily obtained.

Table II. MTF of Source-Detector Combinations

Blackbody at 3000 K

ν_s c/mm	Normal observer: Photopic	Normal observer: Scotopic	Photoelectric detectors: S-10	Photoelectric detectors: S-11	Photoelectric detectors: S-12	Photoelectric detectors: S-20	Photoelectric detectors: CdSe	Photoelectric detectors: Si diode	Vidicon	Photographic emulsions: Blue sensitive	Photographic emulsions: Ortho chromatic	Photographic emulsions: Pan chromatic
50	.9637	.9672	.9650	.9676	.9689	.9632	.9513	.9470	.9607	.9692	.9669	.9648
100	.9273	.9345	.9301	.9352	.9378	.9264	.9027	.8942	.9214	.9384	.9338	.9297
150	.8911	.9018	.8952	.9028	.9067	.8897	.8542	.8415	.8822	.9076	.9007	.8946
200	.8549	.8691	.8603	.8705	.8757	.8530	.8059	.7891	.8431	.8769	.8677	.8596
250	.8189	.8366	.8256	.8383	.8448	.8165	.7580	.7372	.8042	.8462	.8348	.8248
300	.7830	.8042	.7911	.8062	.8139	.7802	.7104	.6858	.7655	.8157	.8020	.7900
350	.7473	.7719	.7567	.7742	.7832	.7441	.6633	.6350	.7271	.7853	.7694	.7554
400	.7118	.7397	.7225	.7424	.7526	.7082	.6167	.5850	.6889	.7550	.7369	.7211
450	.6765	.7077	.6885	.7108	.7222	.6726	.5708	.5358	.6511	.7248	.7046	.6869
500	.6416	.6760	.6548	.6794	.6919	.6373	.5255	.4876	.6136	.6949	.6725	.6531
550	.6069	.6445	.6214	.6482	.6618	.6024	.4811	.4406	.5766	.6651	.6407	.6195
600	.5726	.6132	.5884	.6173	.6320	.5679	.4376	.3949	.5401	.6356	.6091	.5862
650	.5387	.5822	.5557	.5866	.6024	.5337	.3951	.3507	.5040	.6063	.5779	.5533
700	.5052	.5515	.5234	.5562	.5730	.5001	.3537	.3081	.4686	.5772	.5469	.5208
750	.4722	.5211	.4915	.5262	.5440	.4670	.3136	.2674	.4338	.5485	.5163	.4887
800	.4397	.4911	.4601	.4966	.5152	.4345	.2749	.2289	.3997	.5200	.4861	.4571
850	.4077	.4615	.4292	.4673	.4867	.4025	.2378	.1928	.3664	.4919	.4562	.4260
900	.3763	.4323	.3988	.4384	.4587	.3713	.2024	.1599	.3339	.4642	.4269	.3954
950	.3455	.4035	.3691	.4100	.4310	.3408	.1690	.1308	.3024	.4368	.3980	.3654
1000	.3154	.3753	.3400	.3821	.4037	.3111	.1380	.1061	.2719	.4099	.3696	.3361
1050	.2861	.3475	.3116	.3547	.3768	.2822	.1097	.0856	.2424	.3834	.3417	.3074
1100	.2576	.3204	.2840	.3279	.3504	.2544	.0846	.0688	.2142	.3573	.3144	.2795
1150	.2299	.2938	.2572	.3017	.3245	.2275	.0626	.0552	.1875	.3318	.2878	.2524
1200	.2032	.2678	.2313	.2761	.2991	.2018	.0440	.0441	.1624	.3068	.2619	.2261
1250	.1775	.2425	.2064	.2512	.2743	.1775	.0290	.0351	.1391	.2824	.2366	.2008
1300	.1528	.2180	.1825	.2271	.2501	.1547	.0181	.0279	.1178	.2587	.2122	.1765
1350	.1295	.1942	.1599	.2038	.2266	.1337	.0114	.0221	.0987	.2356	.1886	.1533
1400	.1074	.1713	.1388	.1813	.2037	.1145	.0082	.0174	.0817	.2132	.1659	.1314
1450	.0869	.1493	.1192	.1599	.1816	.0974	.0062	.0137	.0668	.1916	.1442	.1108
1500	.0680	.1283	.1014	.1395	.1602	.0822	.0047	.0107	.0540	.1708	.1235	.0918
1550	.0513	.1084	.0853	.1203	.1398	.0690	.0037	.0084	.0432	.1509	.1041	.0747
1600	.0369	.0898	.0711	.1024	.1202	.0575	.0029	.0065	.0341	.1321	.0860	.0600
1650	.0252	.0724	.0587	.0861	.1017	.0476	.0023	.0050	.0266	.1143	.0694	.0479
1700	.0162	.0567	.0480	.0715	.0843	.0392	.0018	.0039	.0205	.0979	.0547	.0383
1750	.0098	.0428	.0389	.0587	.0682	.0320	.0015	.0030	.0156	.0830	.0424	.0308
1800	.0055	.0310	.0313	.0476	.0535	.0260	.0012	.0023	.0118	.0700	.0328	.0248
1850	.0029	.0215	.0249	.0383	.0404	.0210	.0009	.0018	.0089	.0590	.0255	.0201
1900	.0015	.0143	.0197	.0305	.0289	.0168	.0007	.0013	.0066	.0500	.0199	.0164
1950	.0007	.0091	.0155	.0241	.0195	.0134	.0006	.0010	.0049	.0425	.0155	.0134
2000	.0003	.0055	.0120	.0188	.0129	.0105	.0005	.0008	.0036	.0362	.0120	.0108
2050	.0002	.0032	.0093	.0146	.0092	.0082	.0004	.0006	.0026	.0308	.0092	.0087
2100	.0001	.0018	.0071	.0112	.0065	.0063	.0003	.0004	.0019	.0260	.0069	.0069
2150	.0000	.0009	.0053	.0085	.0046	.0048	.0002	.0003	.0014	.0218	.0052	.0054
2200	.0000	.0004	.0040	.0064	.0032	.0036	.0002	.0002	.0010	.0180	.0038	.0042
2250	.0000	.0002	.0029	.0047	.0022	.0027	.0001	.0002	.0007	.0147	.0028	.0032
2300	.0000	.0001	.0021	.0034	.0015	.0020	.0001	.0001	.0004	.0119	.0020	.0024
2350	.0000	.0000	.0015	.0025	.0010	.0014	.0001	.0001	.0003	.0092	.0014	.0018
2400	.0000	.0000	.0010	.0017	.0007	.0010	.0000	.0001	.0002	.0071	.0010	.0013
2450	.0000	.0000	.0007	.0012	.0004	.0007	.0000	.0000	.0001	.0052	.0006	.0009
2500	.0000	.0000	.0005	.0008	.0002	.0004	.0000	.0000	.0001	.0037	.0004	.0006
2550	.0000	.0000	.0003	.0005	.0001	.0003	.0000	.0000	.0000	.0025	.0003	.0004
2600	.0000	.0000	.0002	.0003	.0001	.0002	.0000	.0000	.0000	.0016	.0002	.0002
2650	.0000	.0000	.0001	.0001	.0000	.0001	.0000	.0000	.0000	.0009	.0001	.0001
2700	.0000	.0000	.0000	.0001	.0000	.0000	.0000	.0000	.0000	.0005	.0000	.0001
2750	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0002	.0000	.0000
2800	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000

A. Photoelectric Detection

The output current is given by

$$\begin{aligned} I &= \Phi_e S_0 k_s \\ &= \Phi_v S_0 k_s / K k_v, \end{aligned} \tag{6}$$

where Φ_e, Φ_v are, respectively, the values of radiant and luminous transmitted flux (i.e., flux incident on the detector), and S_0 is the detector sensitivity (at λ_0) in A/W.

B. Photographic Detection

The exposure Q, relative to the reference exposure Q_0, is*

$$\begin{aligned} q = Q/Q_0 &= E_e S_0 t k_s \\ &= E_v S_0 t k_s / K k_v, \end{aligned} \tag{7}$$

*To allow for nonlinearities, the emulsion response is given only relative to a reference exposure. Individual density–log exposure characteristics (H-D curves) must be consulted to translate q into a density difference.

Table II. Continued

Blackbody at 5000 K

ν_s c/mm	Normal observer		Photoelectric detectors							Photographic emulsions		
	Photopic	Scotopic	S–10	S–11	S–12	S–20	CdSe	Si diode	Vidicon	Blue sensitive	Ortho chromatic	Pan chromatic
50	.9643	.9679	.9681	.9698	.9696	.9672	.9537	.9536	.9641	.9721	.9686	.9677
100	.9286	.9358	.9362	.9396	.9393	.9345	.9075	.9072	.9283	.9442	.9372	.9353
150	.8930	.9037	.9043	.9094	.9090	.9018	.8614	.8610	.8925	.9163	.9058	.9031
200	.8575	.8717	.8726	.8793	.8787	.8692	.8156	.8150	.8568	.8885	.8746	.8709
250	.8221	.8398	.8409	.8492	.8485	.8366	.7699	.7693	.8213	.8607	.8433	.8388
300	.7868	.8080	.8093	.8192	.8184	.8042	.7246	.7240	.7858	.8330	.8122	.8068
350	.7517	.7763	.7778	.7894	.7884	.7720	.6798	.6792	.7506	.8054	.7813	.7749
400	.7168	.7448	.7465	.7597	.7586	.7399	.6354	.6348	.7156	.7779	.7504	.7432
450	.6822	.7134	.7154	.7301	.7288	.7080	.5915	.5911	.6809	.7505	.7197	.7117
500	.6478	.6823	.6845	.7007	.6993	.6763	.5483	.5482	.6465	.7233	.6892	.6804
550	.6137	.6513	.6538	.6715	.6699	.6449	.5057	.5060	.6124	.6962	.6589	.6493
600	.5799	.6206	.6234	.6424	.6407	.6138	.4640	.4648	.5786	.6692	.6289	.6185
650	.5465	.5901	.5932	.6137	.6118	.5830	.4232	.4245	.5453	.6424	.5991	.5880
700	.5135	.5600	.5633	.5851	.5831	.5525	.3833	.3855	.5124	.6159	.5696	.5577
750	.4809	.5301	.5338	.5569	.5546	.5224	.3445	.3478	.4800	.5895	.5403	.5279
800	.4489	.5006	.5046	.5289	.5264	.4926	.3070	.3115	.4481	.5634	.5114	.4984
850	.4173	.4714	.4758	.5012	.4986	.4634	.2708	.2770	.4168	.5376	.4829	.4693
900	.3863	.4427	.4475	.4739	.4710	.4346	.2361	.2444	.3861	.5120	.4547	.4406
950	.3558	.4143	.4195	.4469	.4439	.4063	.2030	.2144	.3561	.4867	.4269	.4124
1000	.3261	.3864	.3921	.4204	.4171	.3786	.1719	.1871	.3268	.4617	.3996	.3847
1050	.2970	.3590	.3652	.3942	.3907	.3514	.1431	.1628	.2984	.4370	.3728	.3576
1100	.2687	.3322	.3389	.3685	.3647	.3249	.1169	.1412	.2709	.4127	.3464	.3310
1150	.2412	.3058	.3131	.3433	.3392	.2992	.0933	.1221	.2443	.3887	.3206	.3051
1200	.2145	.2801	.2880	.3186	.3142	.2741	.0728	.1053	.2189	.3652	.2954	.2798
1250	.1888	.2550	.2637	.2945	.2897	.2500	.0556	.0905	.1947	.3421	.2707	.2553
1300	.1642	.2306	.2400	.2709	.2657	.2268	.0422	.0775	.1719	.3194	.2468	.2315
1350	.1406	.2069	.2173	.2480	.2424	.2047	.0329	.0662	.1505	.2973	.2235	.2086
1400	.1183	.1840	.1955	.2258	.2197	.1838	.0273	.0564	.1308	.2756	.2010	.1867
1450	.0974	.1620	.1748	.2043	.1977	.1641	.0231	.0478	.1126	.2545	.1794	.1657
1500	.0781	.1408	.1552	.1836	.1764	.1458	.0196	.0404	.0962	.2340	.1586	.1460
1550	.0605	.1207	.1369	.1638	.1559	.1288	.0168	.0340	.0814	.2141	.1389	.1276
1600	.0451	.1017	.1199	.1449	.1362	.1132	.0144	.0285	.0683	.1950	.1202	.1109
1650	.0322	.0839	.1043	.1272	.1175	.0989	.0124	.0238	.0568	.1766	.1028	.0960
1700	.0218	.0675	.0900	.1107	.0997	.0859	.0106	.0198	.0468	.1591	.0868	.0831
1750	.0139	.0527	.0772	.0956	.0831	.0742	.0091	.0164	.0383	.1425	.0727	.0718
1800	.0084	.0398	.0657	.0818	.0678	.0636	.0077	.0135	.0310	.1271	.0606	.0619
1850	.0048	.0289	.0554	.0695	.0538	.0542	.0066	.0111	.0250	.1131	.0505	.0533
1900	.0026	.0202	.0464	.0585	.0414	.0458	.0055	.0090	.0200	.1003	.0420	.0458
1950	.0014	.0136	.0386	.0488	.0309	.0384	.0046	.0073	.0158	.0887	.0347	.0392
2000	.0007	.0087	.0318	.0404	.0229	.0318	.0039	.0058	.0124	.0781	.0284	.0332
2050	.0004	.0054	.0259	.0331	.0175	.0262	.0032	.0046	.0096	.0683	.0230	.0279
2100	.0002	.0032	.0209	.0268	.0134	.0213	.0026	.0037	.0074	.0593	.0184	.0232
2150	.0001	.0017	.0167	.0215	.0101	.0171	.0021	.0028	.0056	.0509	.0146	.0190
2200	.0000	.0009	.0131	.0170	.0075	.0135	.0017	.0022	.0041	.0432	.0114	.0154
2250	.0000	.0004	.0102	.0132	.0055	.0105	.0013	.0016	.0030	.0361	.0087	.0122
2300	.0000	.0002	.0077	.0102	.0040	.0081	.0010	.0012	.0021	.0297	.0066	.0096
2350	.0000	.0001	.0058	.0076	.0028	.0060	.0008	.0009	.0015	.0239	.0049	.0073
2400	.0000	.0000	.0042	.0056	.0020	.0044	.0006	.0006	.0010	.0188	.0036	.0054
2450	.0000	.0000	.0030	.0040	.0013	.0031	.0004	.0004	.0006	.0143	.0025	.0039
2500	.0000	.0000	.0020	.0027	.0008	.0021	.0003	.0003	.0004	.0105	.0017	.0027
2550	.0000	.0000	.0013	.0018	.0005	.0014	.0002	.0002	.0002	.0073	.0012	.0018
2600	.0000	.0000	.0008	.0011	.0003	.0008	.0001	.0001	.0001	.0048	.0007	.0011
2650	.0000	.0000	.0004	.0006	.0002	.0005	.0001	.0001	.0000	.0029	.0004	.0006
2700	.0000	.0000	.0002	.0003	.0001	.0002	.0000	.0000	.0000	.0015	.0002	.0003
2750	.0000	.0000	.0001	.0001	.0000	.0001	.0000	.0000	.0000	.0006	.0001	.0001
2800	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0002	.0000	.0000

where Q_0 is the exposure (at λ_0) in energy per unit area required to produce the reference density D_0, $S_0 = 1/Q_0$ is the sensitivity, at λ_0, in reciprocal exposure required to produce D_0, E_e is the irradiation, and t is the exposure time. Note that the reference sensitivity of a photographic emulsion may be estimated from the ASA (arithmetic) speed S_x by means of the following formula:

$$S_0(1) = [30 S_x k_v / k_s] \quad (\mathrm{J/m^2})^{-1}, \qquad (8)$$

where D_0 is taken to be unity and the values of $\Delta\lambda$ are those for standard illuminant B, see Appendix.

C. Visual Detection

The luminous efficacy (lm/W) of any source is obtained by simply taking the ratio of Eq. (3a) to Eq. (3):

$$K_v = i_{vT}/i_T = K k_v. \qquad (9)$$

IV. Polychromatic MTF of Perfect Lens

The monochromatic MTF of a perfect lens with circular aperture and incoherent illumination is given by

$$T(y) = (2/\pi)[\cos^{-1} y - y(1 - y^2)^{1/2}], \qquad (10)$$

Table II. Continued

CIE Illuminant A

ν_s c/mm	Normal observer: Photopic	Normal observer: Scotopic	Photoelectric detectors: S–10	S–11	S–12	S–20	CdSe	Si diode	Vidicon	Photographic emulsions: Blue sensitive	Ortho chromatic	Pan chromatic
50	.9636	.9672	.9647	.9673	.9688	.9627	.9531	.9555	.9606	.9689	.9667	.9646
100	.9272	.9343	.9294	.9347	.9376	.9255	.9062	.9111	.9212	.9378	.9334	.9292
150	.8908	.9015	.8941	.9021	.9065	.8883	.8594	.8668	.8819	.9067	.9002	.8939
200	.8546	.8688	.8590	.8696	.8754	.8513	.8129	.8227	.8427	.8758	.8671	.8586
250	.8185	.8362	.8239	.8371	.8444	.8143	.7666	.7788	.8037	.8448	.8340	.8235
300	.7825	.8037	.7890	.8048	.8135	.7776	.7206	.7352	.7649	.8140	.8011	.7885
350	.7467	.7713	.7543	.7726	.7827	.7410	.6750	.6920	.7263	.7833	.7683	.7537
400	.7112	.7391	.7198	.7406	.7520	.7048	.6299	.6491	.6880	.7528	.7357	.7191
450	.6759	.7071	.6855	.7087	.7215	.6687	.5854	.6068	.6501	.7224	.7032	.6848
500	.6408	.6752	.6515	.6771	.6912	.6331	.5415	.5650	.6125	.6921	.6710	.6507
550	.6061	.6436	.6178	.6457	.6610	.5977	.4983	.5238	.5754	.6621	.6390	.6169
600	.5717	.6123	.5845	.6145	.6311	.5628	.4558	.4833	.5388	.6323	.6073	.5834
650	.5378	.5812	.5515	.5837	.6014	.5284	.4143	.4436	.5026	.6028	.5759	.5503
700	.5042	.5504	.5189	.5531	.5720	.4944	.3737	.4047	.4671	.5735	.5448	.5176
750	.4711	.5200	.4868	.5229	.5429	.4610	.3342	.3667	.4322	.5445	.5141	.4853
800	.4385	.4900	.4551	.4931	.5141	.4281	.2958	.3298	.3980	.5159	.4837	.4535
850	.4065	.4603	.4240	.4636	.4856	.3959	.2588	.2941	.3646	.4875	.4538	.4222
900	.3751	.4310	.3935	.4346	.4574	.3644	.2232	.2596	.3320	.4596	.4243	.3915
950	.3443	.4022	.3635	.4060	.4297	.3337	.1893	.2264	.3003	.4320	.3953	.3613
1000	.3141	.3739	.3343	.3780	.4023	.3038	.1571	.1949	.2696	.4049	.3668	.3318
1050	.2848	.3461	.3057	.3505	.3754	.2748	.1268	.1651	.2401	.3782	.3388	.3031
1100	.2562	.3189	.2780	.3235	.3490	.2468	.0989	.1372	.2117	.3520	.3115	.2750
1150	.2285	.2923	.2511	.2972	.3230	.2199	.0736	.1116	.1847	.3263	.2848	.2478
1200	.2018	.2663	.2251	.2715	.2976	.1942	.0514	.0889	.1593	.3012	.2588	.2215
1250	.1761	.2410	.2002	.2466	.2728	.1699	.0334	.0701	.1358	.2767	.2335	.1961
1300	.1515	.2165	.1763	.2224	.2486	.1472	.0204	.0550	.1144	.2528	.2090	.1718
1350	.1281	.1927	.1538	.1991	.2250	.1263	.0124	.0431	.0951	.2297	.1854	.1486
1400	.1061	.1698	.1328	.1766	.2021	.1075	.0088	.0336	.0782	.2072	.1627	.1267
1450	.0856	.1478	.1134	.1552	.1800	.0907	.0065	.0262	.0635	.1856	.1410	.1062
1500	.0669	.1268	.0958	.1349	.1586	.0760	.0049	.0203	.0510	.1648	.1203	.0873
1550	.0502	.1070	.0801	.1158	.1382	.0633	.0038	.0157	.0404	.1449	.1010	.0703
1600	.0359	.0883	.0663	.0981	.1187	.0523	.0029	.0121	.0317	.1261	.0829	.0558
1650	.0244	.0711	.0543	.0819	.1002	.0430	.0023	.0093	.0245	.1085	.0665	.0440
1700	.0156	.0555	.0441	.0676	.0828	.0351	.0018	.0071	.0187	.0922	.0519	.0348
1750	.0094	.0417	.0355	.0551	.0668	.0285	.0014	.0054	.0141	.0775	.0398	.0277
1800	.0052	.0301	.0283	.0444	.0522	.0230	.0011	.0041	.0106	.0647	.0304	.0221
1850	.0027	.0207	.0224	.0354	.0391	.0184	.0009	.0031	.0079	.0541	.0234	.0177
1900	.0013	.0136	.0176	.0280	.0278	.0146	.0007	.0023	.0058	.0455	.0181	.0143
1950	.0007	.0086	.0137	.0219	.0185	.0115	.0006	.0018	.0043	.0385	.0141	.0116
2000	.0003	.0052	.0105	.0170	.0121	.0090	.0004	.0013	.0031	.0326	.0108	.0094
2050	.0002	.0030	.0081	.0131	.0085	.0070	.0003	.0010	.0023	.0276	.0082	.0075
2100	.0001	.0016	.0061	.0100	.0060	.0054	.0003	.0007	.0016	.0233	.0061	.0059
2150	.0000	.0008	.0046	.0075	.0042	.0040	.0002	.0005	.0011	.0194	.0045	.0046
2200	.0000	.0004	.0034	.0056	.0029	.0030	.0001	.0004	.0008	.0160	.0033	.0036
2250	.0000	.0002	.0025	.0041	.0020	.0022	.0001	.0003	.0005	.0131	.0024	.0027
2300	.0000	.0001	.0018	.0030	.0013	.0016	.0001	.0002	.0004	.0105	.0017	.0020
2350	.0000	.0000	.0013	.0021	.0009	.0011	.0001	.0001	.0002	.0082	.0012	.0015
2400	.0000	.0000	.0009	.0015	.0006	.0008	.0000	.0001	.0001	.0063	.0008	.0010
2450	.0000	.0000	.0006	.0010	.0004	.0005	.0000	.0001	.0001	.0046	.0006	.0007
2500	.0000	.0000	.0004	.0007	.0002	.0003	.0000	.0000	.0001	.0033	.0004	.0005
2550	.0000	.0000	.0002	.0004	.0001	.0002	.0000	.0000	.0000	.0022	.0002	.0003
2600	.0000	.0000	.0001	.0002	.0001	.0001	.0000	.0000	.0000	.0014	.0001	.0002
2650	.0000	.0000	.0001	.0001	.0000	.0001	.0000	.0000	.0000	.0008	.0001	.0001
2700	.0000	.0000	.0000	.0001	.0000	.0000	.0000	.0000	.0000	.0004	.0000	.0000
2750	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0002	.0000	.0000
2800	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000

where $y = \nu_0\lambda$ is the reduced spatial frequency, λ is the wavelength, and $\nu_0 = \nu F = n\nu/2A$ is the *specific spatial frequency*, which we have introduced to facilitate the presentation of results. Here, ν is the spatial frequency, F is the effective F/number, n is the refractive index of the medium, and A is the numerical aperture—all of these referring to the image space. For an extensive tabulation of Eq. (10) see Ref. 3, Table 67.

With polychromatic radiation, the effective MTF (T_p) is obtained by forming the weighted average of the monochromatic MTF. Thus we may write:

$$T_p(\nu_0) = \int \tau(\lambda)e(\lambda)s(\lambda)T(\nu_0\lambda)d\lambda \Big/ \int \tau(\lambda)e(\lambda)s(\lambda)d\lambda. \tag{11}$$

Note that the denominator is required for normalization at $\nu_0 = 0$.

Table II. Continued

CIE Illimunant B

ν_x c/mm	Normal observer: Photopic	Normal observer: Scotopic	Photoelectric detectors: S–10	S–11	S–12	S–20	CdSe	Si diode	Vidicon	Photographic emulsions: Blue sensitive	Ortho chromatic	Pan chromatic
50	.9643	.9679	.9673	.9690	.9694	.9663	.9547	.9592	.9638	.9705	.9680	.9667
100	.9285	.9358	.9347	.9381	.9387	.9327	.9096	.9185	.9276	.9410	.9361	.9335
150	.8929	.9037	.9021	.9072	.9081	.8990	.8645	.8779	.8915	.9116	.9042	.9003
200	.8573	.8718	.8695	.8763	.8776	.8655	.8196	.8373	.8555	.8822	.8723	.8671
250	.8219	.8399	.8371	.8455	.8471	.8321	.7749	.7970	.8197	.8529	.8406	.8341
300	.7865	.8081	.8048	.8149	.8168	.7988	.7306	.7570	.7839	.8236	.8089	.8012
350	.7514	.7764	.7726	.7843	.7865	.7656	.6866	.7172	.7484	.7945	.7774	.7684
400	.7165	.7449	.7405	.7539	.7564	.7327	.6431	.6777	.7131	.7655	.7460	.7358
450	.6818	.7135	.7087	.7236	.7264	.6999	.6000	.6386	.6781	.7366	.7148	.7034
500	.6474	.6823	.6771	.6935	.6966	.6674	.5576	.5999	.6434	.7079	.6838	.6712
550	.6132	.6514	.6457	.6636	.6669	.6352	.5157	.5618	.6089	.6793	.6530	.6393
600	.5794	.6207	.6146	.6340	.6375	.6033	.4746	.5242	.5749	.6510	.6224	.6077
650	.5460	.5902	.5838	.6045	.6083	.5717	.4343	.4872	.5413	.6228	.5921	.5763
700	.5130	.5601	.5533	.5754	.5793	.5405	.3949	.4508	.5081	.5949	.5621	.5453
750	.4804	.5302	.5231	.5465	.5507	.5096	.3564	.4153	.4754	.5673	.5324	.5147
800	.4483	.5007	.4934	.5179	.5223	.4792	.3191	.3805	.4433	.5399	.5031	.4845
850	.4167	.4716	.4640	.4897	.4942	.4493	.2829	.3466	.4118	.5128	.4741	.4547
900	.3856	.4428	.4351	.4618	.4664	.4199	.2480	.3137	.3808	.4860	.4455	.4253
950	.3552	.4145	.4067	.4344	.4391	.3910	.2146	.2819	.3506	.4595	.4174	.3965
1000	.3254	.3866	.3788	.4073	.4121	.3627	.1828	.2513	.3212	.4334	.3897	.3682
1050	.2963	.3592	.3514	.3807	.3855	.3351	.1528	.2220	.2925	.4077	.3625	.3405
1100	.2679	.3323	.3247	.3546	.3593	.3082	.1248	.1942	.2648	.3825	.3358	.3134
1150	.2404	.3060	.2986	.3289	.3337	.2820	.0992	.1681	.2380	.3576	.3097	.2870
1200	.2138	.2803	.2732	.3039	.3085	.2567	.0764	.1441	.2124	.3332	.2842	.2613
1250	.1881	.2552	.2485	.2794	.2839	.2323	.0572	.1227	.1880	.3094	.2593	.2364
1300	.1634	.2308	.2247	.2556	.2598	.2089	.0424	.1042	.1651	.2861	.2351	.2124
1350	.1399	.2071	.2018	.2324	.2364	.1867	.0321	.0880	.1436	.2633	.2117	.1893
1400	.1176	.1842	.1800	.2100	.2136	.1658	.0260	.0740	.1239	.2412	.1891	.1672
1450	.0967	.1621	.1593	.1883	.1915	.1463	.0215	.0620	.1059	.2197	.1673	.1462
1500	.0774	.1410	.1398	.1676	.1701	.1283	.0179	.0517	.0896	.1989	.1466	.1265
1550	.0600	.1209	.1217	.1478	.1496	.1118	.0149	.0429	.0751	.1789	.1268	.1083
1600	.0446	.1018	.1051	.1290	.1299	.0967	.0125	.0354	.0623	.1598	.1082	.0919
1650	.0317	.0840	.0898	.1115	.1112	.0831	.0105	.0291	.0512	.1416	.0909	.0776
1700	.0214	.0676	.0761	.0953	.0935	.0708	.0088	.0237	.0415	.1244	.0752	.0654
1750	.0137	.0528	.0638	.0805	.0770	.0598	.0073	.0192	.0333	.1085	.0614	.0549
1800	.0083	.0399	.0530	.0673	.0617	.0501	.0061	.0154	.0265	.0941	.0499	.0460
1850	.0047	.0290	.0435	.0556	.0479	.0415	.0050	.0123	.0208	.0813	.0404	.0385
1900	.0026	.0203	.0354	.0454	.0357	.0340	.0041	.0097	.0162	.0701	.0325	.0320
1950	.0014	.0136	.0283	.0365	.0255	.0275	.0033	.0076	.0124	.0603	.0260	.0265
2000	.0007	.0087	.0223	.0289	.0178	.0219	.0026	.0058	.0093	.0516	.0204	.0217
2050	.0004	.0053	.0174	.0226	.0129	.0172	.0021	.0044	.0069	.0440	.0158	.0175
2100	.0002	.0030	.0133	.0174	.0093	.0133	.0016	.0033	.0050	.0372	.0120	.0139
2150	.0001	.0016	.0100	.0132	.0066	.0101	.0012	.0024	.0036	.0312	.0089	.0109
2200	.0000	.0008	.0074	.0098	.0046	.0076	.0009	.0017	.0025	.0258	.0065	.0084
2250	.0000	.0003	.0054	.0072	.0031	.0055	.0007	.0012	.0017	.0210	.0047	.0063
2300	.0000	.0001	.0039	.0052	.0021	.0040	.0005	.0008	.0011	.0168	.0033	.0047
2350	.0000	.0000	.0027	.0037	.0014	.0028	.0004	.0006	.0007	.0132	.0023	.0034
2400	.0000	.0000	.0019	.0026	.0009	.0020	.0003	.0004	.0004	.0102	.0016	.0024
2450	.0000	.0000	.0013	.0018	.0005	.0013	.0002	.0002	.0003	.0076	.0011	.0017
2500	.0000	.0000	.0008	.0012	.0003	.0009	.0001	.0002	.0001	.0055	.0007	.0011
2550	.0000	.0000	.0005	.0007	.0002	.0006	.0001	.0001	.0001	.0038	.0005	.0008
2600	.0000	.0000	.0003	.0004	.0001	.0003	.0000	.0001	.0000	.0025	.0003	.0005
2650	.0000	.0000	.0002	.0002	.0001	.0002	.0000	.0000	.0000	.0015	.0002	.0003
2700	.0000	.0000	.0001	.0001	.0000	.0001	.0000	.0000	.0000	.0008	.0001	.0001
2750	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0003	.0000	.0000
2800	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0001	.0000	.0000

V. Description of Tables

Equation (11) was evaluated for six common light sources and twelve common detectors. Blackbody radiators at 3000 K and 5000 K (Ref. 3, Table 20), standard illuminants A and B (Ref. 3, Table 11) and CRT phosphors P–11 and P–16 were included among the sources. The detectors include the standard photopic and scotopic visibility curves (CIE, 1931, Ref. 3, Table 2 and 1951, Ref. 4, respectively) photoelectric detectors S–10, S–11, S–12, and S–20 (Ref. 5), CdSe, silicon solar cell, vidicon, and three representative photographic emulsions: blue-sensitive, orthochromatic, and panchromatic. Note that only the first four radiators and the first six detectors have standardized characteristics. The characteristics of the others were taken from manufacturers' data covering representative specimen.* These are known only to two significant figures.

*The phosphor response curve data were taken from JEDEC Publication No. 16 (Electronic Industries Association, Washington, D.C., 1960). The cadmium selenide and silicon photodiode sensitivity curves were taken from (modified) data published for the Clairex Type 3 detector and EG & G, Inc., SD–100 photodiode, respectively. The vidicon curve was taken from data published for the RCA Type 2 surface. The photographic sensitivity data are based on curves made available by Eastman Kodak Co. for their high resolution plates, Royal Ortho film, and Panatomic-X films. These data should be taken as representative only. Note that S–10 is a representative image orthicon curve and S–12 a representative CdS curve.

Table II, Continued

P–11 Phosphor

ν_s c/mm	Normal observer: Photopic	Normal observer: Scotopic	Photoelectric detectors: S–10	S–11	S–12	S–20	CdSe	Si diode	Vidicon	Photographic emulsions: Blue sensitive	Ortho chromatic	Pan chromatic
50	.9675	.9692	.9701	.9702	.9696	.9703	.9700	.9697	.9696	.9701	.9699	.9701
100	.9350	.9385	.9403	.9405	.9391	.9405	.9400	.9395	.9393	.9401	.9398	.9403
150	.9025	.9078	.9105	.9108	.9087	.9109	.9101	.9093	.9090	.9102	.9098	.9105
200	.8701	.8771	.8807	.8811	.8784	.8812	.8802	.8791	.8788	.8804	.8798	.8807
250	.8378	.8465	.8510	.8515	.8481	.8516	.8504	.8490	.8486	.8506	.8498	.8510
300	.8056	.8160	.8214	.8220	.8180	.8221	.8207	.8190	.8185	.8210	.8200	.8214
350	.7735	.7856	.7919	.7926	.7879	.7928	.7911	.7891	.7885	.7914	.7902	.7919
400	.7416	.7554	.7625	.7633	.7579	.7635	.7616	.7593	.7587	.7619	.7606	.7625
450	.7098	.7253	.7333	.7341	.7281	.7343	.7322	.7297	.7290	.7326	.7311	.7333
500	.6783	.6953	.7042	.7051	.6985	.7054	.7030	.7002	.6994	.7034	.7018	.7042
550	.6470	.6656	.6753	.6763	.6690	.6765	.6739	.6709	.6700	.6744	.6727	.6753
600	.6159	.6360	.6465	.6476	.6398	.6479	.6451	.6418	.6409	.6456	.6437	.6465
650	.5851	.6067	.6180	.6192	.6107	.6195	.6165	.6129	.6119	.6170	.6150	.6180
700	.5546	.5776	.5897	.5910	.5819	.5913	.5881	.5843	.5832	.5887	.5865	.5897
750	.5244	.5488	.5617	.5630	.5534	.5633	.5599	.5559	.5548	.5605	.5582	.5617
800	.4945	.5203	.5339	.5353	.5251	.5356	.5320	.5278	.5266	.5327	.5303	.5339
850	.4651	.4921	.5064	.5078	.4972	.5082	.5044	.5000	.4987	.5052	.5026	.5064
900	.4360	.4643	.4792	.4807	.4696	.4811	.4772	.4725	.4712	.4779	.4753	.4792
950	.4074	.4368	.4523	.4539	.4423	.4544	.4502	.4454	.4440	.4510	.4482	.4524
1000	.3792	.4097	.4258	.4275	.4154	.4280	.4237	.4186	.4172	.4245	.4216	.4259
1050	.3516	.3830	.3997	.4014	.3889	.4019	.3975	.3922	.3908	.3984	.3954	.3998
1100	.3245	.3568	.3740	.3758	.3628	.3763	.3717	.3663	.3648	.3726	.3695	.3741
1150	.2979	.3310	.3487	.3505	.3372	.3511	.3464	.3408	.3393	.3473	.3441	.3489
1200	.2720	.3057	.3239	.3258	.3121	.3263	.3215	.3158	.3143	.3225	.3192	.3241
1250	.2467	.2810	.2996	.3015	.2875	.3020	.2971	.2913	.2897	.2982	.2948	.2998
1300	.2222	.2569	.2758	.2777	.2634	.2782	.2733	.2674	.2658	.2744	.2709	.2760
1350	.1984	.2334	.2525	.2544	.2400	.2550	.2500	.2440	.2424	.2512	.2476	.2528
1400	.1754	.2105	.2298	.2318	.2171	.2324	.2273	.2213	.2197	.2285	.2250	.2302
1450	.1533	.1883	.2078	.2098	.1950	.2104	.2053	.1993	.1976	.2065	.2029	.2082
1500	.1321	.1669	.1865	.1884	.1735	.1890	.1840	.1779	.1762	.1852	.1816	.1869
1550	.1119	.1463	.1658	.1678	.1528	.1684	.1634	.1573	.1557	.1647	.1611	.1664
1600	.0929	.1265	.1460	.1479	.1330	.1485	.1436	.1376	.1359	.1449	.1413	.1466
1650	.0752	.1077	.1270	.1288	.1140	.1295	.1246	.1188	.1171	.1260	.1224	.1277
1700	.0588	.0900	.1089	.1107	.0960	.1113	.1066	.1009	.0993	.1081	.1046	.1097
1750	.0441	.0734	.0918	.0935	.0791	.0942	.0897	.0842	.0826	.0912	.0878	.0928
1800	.0315	.0581	.0758	.0774	.0633	.0782	.0740	.0687	.0672	.0755	.0722	.0771
1850	.0211	.0443	.0612	.0626	.0489	.0634	.0595	.0547	.0532	.0612	.0581	.0628
1900	.0133	.0323	.0480	.0493	.0360	.0500	.0466	.0422	.0409	.0485	.0455	.0500
1950	.0079	.0223	.0364	.0375	.0250	.0383	.0353	.0315	.0303	.0375	.0346	.0387
2000	.0044	.0144	.0266	.0274	.0165	.0282	.0258	.0225	.0216	.0283	.0253	.0290
2050	.0023	.0087	.0185	.0192	.0109	.0198	.0180	.0154	.0147	.0207	.0176	.0209
2100	.0011	.0048	.0122	.0127	.0069	.0133	.0119	.0100	.0094	.0147	.0116	.0143
2150	.0005	.0023	.0076	.0079	.0040	.0083	.0074	.0060	.0057	.0100	.0071	.0093
2200	.0002	.0010	.0044	.0046	.0022	.0049	.0044	.0034	.0032	.0064	.0041	.0057
2250	.0001	.0004	.0024	.0024	.0011	.0026	.0024	.0018	.0016	.0039	.0022	.0032
2300	.0000	.0001	.0012	.0012	.0005	.0013	.0012	.0009	.0008	.0022	.0011	.0017
2350	.0000	.0000	.0005	.0005	.0002	.0006	.0005	.0004	.0003	.0011	.0005	.0008
2400	.0000	.0000	.0002	.0002	.0001	.0002	.0002	.0001	.0001	.0005	.0002	.0003
2450	.0000	.0000	.0001	.0001	.0000	.0001	.0001	.0000	.0000	.0002	.0001	.0001
2500	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2550	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2600	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2650	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2700	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2750	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2800	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000

The values of $e(\lambda)$ and $s(\lambda)$ used are tabulated in Table I, and results for Eq. (11) in Table II. Table I is included for reader convenience.

To make a broad coverage feasible, simplifying assumptions had to be made concerning $\tau(\lambda)$. This was set equal to unity above $\lambda = 0.35\ \mu$ and equal to zero below this value.* For some sources and detectors data were not available over this full spectral range. Such data were then estimated by extrapolation, the results being enclosed in parenthesis in Table I.

In considering Eqs. (6)–(8), the reader will note that, in addition to the input radiation, only the values of the efficacies, k_s and k_v, are required. These are tabulated in Table III, together with photopic and scotopic luminous efficacies in lm/W. The reference wavelength λ_0, used for the detectors, is also given; manufacturers' data should be consulted for detector sensitivity S_0 at this wavelength.

*This was considered to be a reasonable compromise value, since most glasses absorb strongly below 0.35 μ. Also note that some sources (the standard illuminants) are not defined below this value and others (the phosphors and the 3000 K blackbody) have little output there. Thus the choice of the cutoff point could affect significantly only the 5000 K blackbody radiator.

VI. Recalibration of Photometers

Photometers are frequently calibrated in photometric rather than radiometric units. Unless the spectral

Table II. Continued

P–16 Phosphor

ν_s c/mm	Normal observer		Photoelectric detectors							Photographic emulsions		
	Photopic	Scotopic	S–10	S–11	S–12	S–20	CdSe	Si diode	Vidicon	Blue sensitive	Ortho chromatic	Pan chromatic
50	.9713	.9722	.9749	.9749	.9744	.9749	.9750	.9746	.9744	.9757	.9748	.9751
100	.9427	.9443	.9497	.9498	.9488	.9498	.9500	.9493	.9488	.9514	.9495	.9502
150	.9141	.9165	.9246	.9248	.9232	.9248	.9251	.9240	.9232	.9272	.9243	.9254
200	.8855	.8888	.8996	.8998	.8976	.8997	.9002	.8987	.8977	.9029	.8992	.9005
250	.8570	.8611	.8745	.8748	.8721	.8747	.8753	.8734	.8722	.8787	.8740	.8757
300	.8285	.8334	.8495	.8499	.8467	.8498	.8505	.8483	.8467	.8546	.8490	.8510
350	.8002	.8059	.8246	.8250	.8213	.8249	.8257	.8231	.8214	.8305	.8240	.8263
400	.7720	.7784	.7998	.8002	.7960	.8001	.8010	.7980	.7961	.8064	.7990	.8017
450	.7438	.7510	.7750	.7755	.7707	.7754	.7763	.7731	.7708	.7825	.7741	.7771
500	.7158	.7238	.7503	.7508	.7456	.7507	.7518	.7482	.7457	.7586	.7494	.7527
550	.6880	.6967	.7257	.7263	.7206	.7262	.7274	.7234	.7207	.7348	.7247	.7283
600	.6603	.6698	.7012	.7019	.6956	.7017	.7030	.6987	.6958	.7111	.7001	.7041
650	.6328	.6430	.6769	.6776	.6709	.6774	.6788	.6742	.6710	.6875	.6757	.6799
700	.6055	.6164	.6527	.6534	.6462	.6533	.6547	.6498	.6464	.6641	.6514	.6559
750	.5785	.5900	.6286	.6294	.6217	.6292	.6308	.6255	.6219	.6407	.6272	.6321
800	.5516	.5638	.6047	.6055	.5974	.6053	.6070	.6014	.5976	.6175	.6032	.6084
850	.5250	.5379	.5809	.5818	.5733	.5816	.5834	.5775	.5734	.5945	.5794	.5848
900	.4987	.5122	.5574	.5583	.5493	.5581	.5599	.5537	.5495	.5716	.5558	.5614
950	.4727	.4867	.5340	.5349	.5256	.5348	.5367	.5302	.5257	.5489	.5323	.5382
1000	.4469	.4616	.5108	.5118	.5020	.5116	.5136	.5069	.5022	.5264	.5091	.5152
1050	.4216	.4367	.4878	.4889	.4787	.4887	.4908	.4837	.4789	.5040	.4860	.4925
1100	.3965	.4122	.4651	.4662	.4557	.4660	.4682	.4609	.4559	.4819	.4632	.4699
1150	.3719	.3880	.4426	.4437	.4329	.4435	.4458	.4382	.4331	.4600	.4407	.4476
1200	.3476	.3641	.4204	.4215	.4103	.4213	.4236	.4159	.4105	.4383	.4184	.4255
1250	.3237	.3406	.3984	.3996	.3881	.3994	.4018	.3938	.3883	.4168	.3964	.4037
1300	.3003	.3176	.3768	.3780	.3662	.3777	.3802	.3720	.3664	.3957	.3747	.3821
1350	.2774	.2949	.3554	.3566	.3446	.3564	.3589	.3505	.3447	.3747	.3532	.3609
1400	.2550	.2727	.3343	.3356	.3233	.3354	.3379	.3293	.3235	.3541	.3322	.3400
1450	.2331	.2510	.3136	.3149	.3024	.3146	.3173	.3085	.3025	.3337	.3114	.3193
1500	.2118	.2298	.2932	.2946	.2818	.2943	.2970	.2881	.2820	.3137	.2910	.2991
1550	.1910	.2092	.2733	.2746	.2617	.2743	.2770	.2680	.2619	.2940	.2710	.2791
1600	.1710	.1891	.2537	.2550	.2420	.2547	.2575	.2484	.2421	.2746	.2514	.2596
1650	.1516	.1696	.2345	.2358	.2227	.2355	.2383	.2291	.2228	.2556	.2322	.2405
1700	.1329	.1508	.2157	.2171	.2039	.2168	.2196	.2104	.2040	.2370	.2134	.2217
1750	.1151	.1326	.1974	.1988	.1857	.1985	.2013	.1921	.1857	.2188	.1951	.2035
1800	.0981	.1153	.1796	.1810	.1679	.1807	.1835	.1743	.1679	.2010	.1773	.1857
1850	.0821	.0987	.1623	.1637	.1507	.1634	.1662	.1570	.1507	.1837	.1601	.1683
1900	.0671	.0830	.1456	.1470	.1341	.1467	.1495	.1403	.1341	.1668	.1433	.1516
1950	.0533	.0683	.1295	.1308	.1182	.1305	.1333	.1243	.1181	.1505	.1272	.1353
2000	.0409	.0546	.1139	.1153	.1029	.1150	.1177	.1088	.1027	.1346	.1118	.1197
2050	.0302	.0422	.0991	.1004	.0885	.1001	.1028	.0941	.0882	.1194	.0970	.1047
2100	.0213	.0313	.0850	.0863	.0748	.0860	.0886	.0802	.0744	.1047	.0830	.0904
2150	.0141	.0219	.0717	.0730	.0621	.0726	.0752	.0671	.0616	.0907	.0698	.0769
2200	.0086	.0143	.0593	.0605	.0504	.0602	.0626	.0550	.0497	.0774	.0576	.0642
2250	.0047	.0084	.0479	.0490	.0397	.0487	.0510	.0439	.0390	.0649	.0463	.0524
2300	.0023	.0044	.0376	.0386	.0303	.0383	.0405	.0340	.0295	.0532	.0362	.0416
2350	.0010	.0019	.0285	.0294	.0222	.0291	.0311	.0253	.0213	.0425	.0274	.0320
2400	.0004	.0007	.0208	.0216	.0156	.0213	.0230	.0181	.0147	.0328	.0199	.0237
2450	.0001	.0003	.0144	.0151	.0103	.0148	.0163	.0123	.0095	.0244	.0139	.0168
2500	.0000	.0001	.0094	.0099	.0064	.0097	.0108	.0078	.0056	.0171	.0092	.0112
2550	.0000	.0000	.0058	.0062	.0037	.0060	.0068	.0046	.0031	.0114	.0057	.0070
2600	.0000	.0000	.0031	.0034	.0019	.0033	.0038	.0024	.0014	.0068	.0032	.0040
2650	.0000	.0000	.0016	.0017	.0009	.0017	.0020	.0012	.0006	.0037	.0017	.0020
2700	.0000	.0000	.0006	.0007	.0004	.0007	.0008	.0005	.0002	.0017	.0007	.0009
2750	.0000	.0000	.0002	.0002	.0001	.0002	.0002	.0001	.0000	.0005	.0002	.0002
2800	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0001	.0000	.0000

response of the meter matches that of the normal observer, such calibration is generally valid only for radiation, matching that used during the original calibration procedure. When the meter is used with radiation having a different spectral distribution, it must be recalibrated. The required recalibration factor (C) is readily expressed in terms of the system efficacies involved.[2] Reference to Eq. (5a) shows that this factor is

$$C = \frac{R}{R_c} \frac{k_s/k_v}{(k_s/k_v)_c}, \qquad (12)$$

where the subscript C refers to parameters of the original calibrating system.

Manufacturers of such equipment would significantly add to the value of their product if they would publish values of C for various sources with which their meters are likely to be used.

Appendix. Reference Sensitivity of Photographic Emulsions

The reference sensitivity of photographic emulsions may be obtained by means of the following considerations.

The (arithmetic) speed of the photographic emulsion is defined by[6]

$$S_x = 0.8/Q_m, \qquad \text{(A-1)}$$

Table III. System Efficiencies of Source–Detector Combinations

		Normal observer: Photopic	Normal observer: Scotopic	Photoelectric detectors: S–10	Photoelectric detectors: S–11	Photoelectric detectors: S–12	Photoelectric detectors: S–20	Photoelectric detectors: CdSe	Photoelectric detectors: Si diode	Vidicon	Photographic emulsions: Blue sensitive	Photographic emulsions: Ortho chromatic	Photographic emulsions: Pan chromatic	Luminous efficacies: Photopic (lm/W)	Luminous efficacies: Scotopic (sc. lm/W)
Blackbody	3000°K	.0303	.0180	.0414	.0269	.0055	.0483	.0481	.2794	.0704	0.016	0.049	0.045	20.6	31.4
	5000°K	.1192	.1028	.2275	.1847	.0389	.2366	.0871	.4918	.2594	0.142	0.291	0.235	81.0	179.6
Standard illuminants[a]	A	.1777	.1008	.2380	.1497	.0302	.2833	.2563	.8254	.4157	0.085	0.273	0.259	120.8	176.0
	B	.2565	.2196	.4493	.3526	.0799	.4682	.1697	.7379	.5479	0.219	0.580	0.454	174.4	383.5
Phosphors (JEDEC)	P–11	.2010	.6033	.9504	.9159	.2701	.8783	.0401	.5371	.7306	0.429	1.243	0.688	136.7	1053.4
	P–16	.0032	.0424	.8593	.8858	.0945	.9057	.0400	.3292	.3615	1.341	0.941	0.969	2.2	74.1
REFERENCE WAVELENGTH		.5550	.5070	.4500	.4400	.5020	.4200	.7400	.9400	.5500	.4000	.4000	.4000		

[a] The spectral characteristics of Illuminants A and B (CIE, 1931) are roughly similar to those of blackbodies at 3000 K and 5000 K, respectively, except that they are defined only over the visible portion of the spectrum. Thus, in the present table, they correspond approximately to such blackbody radiators—with the input energy sharply cut off outside the wavelength range 0.35–0.78 μ.

where Q_m is the luminous exposure (in m cd sec) required to produce a density of 0.1 above the fog level; the slope of the H and D curve is such that $10^{1.3}Q_m$ is required to produce a density of 0.9, and the radiation to be used in the exposure is similar to standard Illuminant B.

Thus, to produce unity density, an exposure of approximately $E_v t = 10^{1.3\times 9/8}Q_m = 28.84Q_m = (23/S_x)$ m cd sec is required.

Substituting this value into Eq. (7), setting $q = 1$, and using Eq. (A-1), we find $S_0 = (K/23)S_x(\Delta_v\lambda/\Delta_s\lambda)$. With $K = 680$ lm/W, Eq. (8) results.

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