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Sensitometry in Canadian Aerial Survey

The NRC Sensitometer, its design goals, its design features and reasons for their choice, some evolutionary changes, methods of calibration and verification, and some of the sensitometric studies it has facilitated, are described.

Abstract: *The advantages of sensitometric control of the processing of aerial films became apparent and was brought into common use in Canada about 1943, first by the Royal Canadian Air Force and later by private companies. A sensitometer specifically for this purpose was designed at the National Research Council in 1956-57. Some 20 to this design are now in use by various survey organizations. The sensitometer provides light with a spectral energy distribution simulating aerial photographic daylight defined from 340 to 920 nm at an exposure time of 1/120 second. Details of the design and reasons for their choice are discussed. The sensitometers are recalibrated annually, or their calibration verified by a photographic procedure which has been developed. Problems as well as successes of the sensitometer are discussed, and some of the uses that have been made of the sensitometric control are described.*

Introduction

Sensitometric control of aerial photography is needed for consistent optimized quality. A sensitometric exposure on every roll of film provides a continuing check of film and processing, accumulates a useful background of information, and aids early detection and correction of any problems. Advance knowledge of the speeds and gradients of the actual films available, under various conditions of development, permits optimum selection of film, development, lens aperture, shutter speed, and filter to suit the scene and flight conditions expected (Carman, 1967; Carman and Brown, 1970). If camera characteristics such as T-numbers versus field angles (International Society for Photogrammetry, 1964), shutter times, and filter transmittance are known, sensitometric data permit conversion of negative densities to scene luminances (radiances).

These advantages became apparent in Canada at least as early as 1943, and it was found possible to introduce sensitometric control of processing of aerial negatives. At that time most of the aerial photography was done by the Royal Canadian Air Force. They encountered occasional problems in diagnosing negative faults. For example, thin negatives might be variously blamed on under exposure, under development, or defective film, with no clear evidence for a choice. This problem was submitted to the Joint RCAF-NRC Photographic Research Committee, which recommended printing a calibrated sensitometric exposure on every roll of film. Sensitometers for this use were calibrated in absolute terms by the National Research Council's Optics Laboratory so that actual, not just relative, log exposure values were known and film speeds as well as gamma or average gradient could be derived when the resulting densities were measured and sensitometric curves plotted.

A variety of sensitometers, some made by NRC, some from commercial sources, were used by the Photographic Establishment until about 1957. They suffered from a variety of problems—unrealistically slow shutter speeds, shutter speed variations, and mechanical or electrical unreliability—but proximity to the repair and recalibra-

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tion facilities at NRC enabled them to perform adequately.

Satisfactory densitometers were obtained from commercial sources. To provide for their calibration, a standard densitometer of the inverse-square-law integrating-sphere type was built at NRC. Photographic step tablets measured on it were used to check the commercial instruments. Several type of densitometers, both visual and photoelectric, were found to be suitable. Some were not satisfactory, mainly because the geometries of their optical systems were not such as to measure singly diffuse density.

In the 1950's, the taking of photographs for aerial survey purposes moved from the RCAF to a number of private companies. It then appeared desirable that these companies should be able to obtain sensitometers which would maintain calibration and operate reliably without easy access to specialized repair facilities. In 1956-57, the NRC Optics Section, Physics Design Office, and Physics Workshop designed an instrument aimed at filling this need and constructed a prototype. Some 20 further sensitometers have since been built from these plans by various organizations for the aerial survey companies and for some other users. These sensitometers are now used throughout the industry to provide uniform exposure and processing control information on every roll of aerial film which is acquired by the federal Interdepartmental Committee on Air Surveys (ICAS) and which is stored in the National Air Photo Library.

This report will describe the sensitometer, its design goals, its design features and reasons for their choice, some evolutionary changes, methods of calibration and verification, and some of the sensitometric studies it has facilitated.

THE NRC SENSITOMETER DESIGN GOALS

Design objectives which seemed desirable for survey company use were the following:

- Simple construction
- Capability of placing exposure anywhere on aerial film
- Exposure range of 3 log units (1000:1) in steps of about 0.15(1.4:1), minimum dimension of each step at least 5 mm
- Easy portability by car or light plane
- Adequate spectral simulation of daylight
- Facility for added filter
- Practical shutter speed
- Maintenance of calibration—particularly a fail-safe shutter
- Simplicity of complete calibration
- Mechanical and electrical reliability

Design Features

One of the sensitometers is shown in Figure 1 and the interior arrangement is illustrated in Figure 2. Light is provided by a tungsten lamp

Fig. 1. One of the NRC Sensitometers, with film rewinds and electrical auxiliaries.

operating at a calibrated voltage. The light is converted to a spectral approximation of daylight by a filter, and is directed upward to the film plane by a totally reflecting prism. Light falls on the film to be exposed through a 21-step step tablet (Kodak #2 or similar) set flush with the top face of the instrument where the film is held in contact by a magnetically actuated pressure pad. A gravity-driven sector shutter provides a precisely reproducible exposure time. The incident light can be further modified by the addition of other filters, for example, aerial camera filters for situations where data are sought for specific film-filter combinations. The generous top surface and throat depth of 38 cm (15 inches) allows any area of the aerial film to be easily positioned for exposure. If it is desired

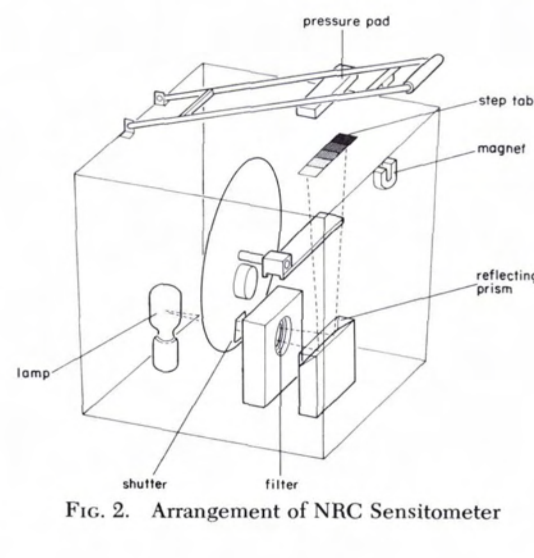

Fig. 2. Arrangement of NRC Sensitometer

to place an exposure toward the far edge of the film, it can be brought forward over the magnet, which will operate through it. The instrument's size is a box 43 by 51 by 51 cm high (17 by 20 by 20 inches) plus various handles and knobs. It weighs about 25 kg (55 lbs). The choice of the quite traditional configuration is explained by the considerations that went into the choice of the various components.

LIGHT SOURCE

A steadily-burning tungsten-filament incandescent lamp, the characteristics of which have long been well known, was chosen as the light source. The spectral distribution of energy with wavelength is smooth, stable, and consistent. Calibration is easily carried out by means of comparison with reference standards which are themselves special tungsten lamps. One alternative, the use of a gas-discharge flash source, would have involved difficulties in matching the spectral energy distribution of the source to that of air photo daylight through its full range into the infrared, and the complexity of absolute spectroradiometric calibration of such a short-duration flash (Goncz, 1966; Gruber, 1977). An arrangement using two tungsten lamps, as suggested by Marriage (1955) and developed by Thiels (1960), permits a much more compact instrument, but introduces complexities of shutter design and filtering not encountered in the NRC design.

The light source used is a DMX projection lamp. This lamp, in projection use, operates on 120 volts and 500 watts at a color temperature of 3200 K with a nominal life of 50 hours. For use in the sensitometer, the lamps are aged for 24 hours at 100 volts and then individually calibrated to run at a color temperature of 2856 K. This occurs typically at about 90 volts and 300 watts, with a life of about 2000 hours, calculated on the basis that life is inversely proportional to the 13th power of the voltage (General Electric, 1956). Lamp depreciation would not be expected to reduce the horizontal candle-power by more than 1 percent in 200 hours of operation. To make a single sensitometric exposure on one film requires that the lamp and its auxiliaries be warmed up for 5 to 7 minutes to become stable. Further time for film handling suggests a total lamp-on time of about 10 minutes. This could be done 1200 times in the 200 hours of lamp operation, which thus corresponds to many years of use by an aerial survey company. In view of this, provision was *not* made for easy lamp replacement by the owner. For one sensitometer, where even more hours of stable operation were desired, a tungsten halogen lamp (Sylvania 500 Q/CL) was used. The spectral power distribution of the particular lamp was measured to make sure that the gas filling did not significantly alter the distribution usual for incandescent tungsten.

When lamp choice was first being made, it was noted that some of the DMX lamps produced asymmetrical illumination distributions in the direction parallel to the lamp axis, which is also the direction of the axes of its six parallel co-planar filament coils. [The effect was later described by Barbrow and Wilson (1958).] Initially this asymmetry was eliminated by diffusion achieved by sandblasting the outside of the bulbs. Later the problem of asymmetrical illumination from clear bulbs was re-examined and it was found practical to measure the illuminance distribution from a number of clear bulbs and by selection obtain adequate quantities which gave satisfactory uniformity. With clear bulbs having an approximately 1 cm square filament area, the 1/120 second shutter gives an efficiency of 72 percent. Exposure level, with the daylight filter but before installation of the step tablet, is typically about 1.0 lux·second.

The lamp is cooled by a fully light-baffled air inlet and outlet with a blower pulling air out. Suction is used rather than pressure so that any air leaking into the sensitometer will be drawn to the lamp house and out rather than having hot air from the lamp spreading into the sensitometer, warming it and especially the filter.

To ensure uniformity of illumination over the length of the step tablet, a feature needed for straight-forward calibration, it was considered desirable to hold the fall-off due to the $\cos^4$ law from center to end of the tablet to 1 percent. This limits the semi-angle subtended by the tablet length at the lamp to $\cos^{-1}(0.99^{1/4}) = 4.06°$. The step tablet has 21 steps of 5 mm width. Consequently, from the center of the tablet to the center of either end step is 5 cm. Thus, the tablet-to-lamp distance is established as $5/\tan 4.06° = 70$ cm (28 in.) approximately.

SPECTRAL QUALITY OF ILLUMINATION

The light from the tungsten lamp, operating at 2856 K, is converted to an approximation of daylight by a filter. Earlier filters were a single piece of Corning 5900 glass, adjusted in thickness to provide adequate correction for use with panchromatic black-and-white films. Later it became desirable, because of the wider variety of films in use, to provide a good approximation to aerial photographic daylight over a wide spectral region from 340 nm in the near ultraviolet to 920 nm in the infrared. The desirable relative spectral energy distribution was defined in Canadian Standards Association Z7.3.2.1-1969 Sensitometry of Monochrome Aerial Films. It is reproduced in Table 1 and in the solid curve of Figure 3. A satisfactory approximation to it was achieved, as illustrated by the dotted curve of Figure 3, by three-component glass filters (Carman, 1969; Wright, 1969). Recently, use has been made of filters com-

TABLE 1. AIR PHOTO DAYLIGHT

λ (nm)	Relative energy	λ (nm)	Relative energy	λ (nm)	Relative energy	λ (nm)	Relative energy
340		470	0.851	620	0.906	770	0.672
and	0.000	480	0.910	630	0.864	780	0.637
below		490	0.892	640	0.866	790	0.646
350	0.002	500	0.936	650	0.830	800	0.597
360	0.003	510	0.950	660	0.837	810	0.516
370	0.005	520	0.954	670	0.864	820	0.571
380	0.021	530	1.008	680	0.824	830	0.599
390	0.056	540	1.002	690	0.733	840	0.587
400	0.188	550	1.015	700	0.749	850	0.574
410	0.329	560	0.990	710	0.773	860	0.551
420	0.414	570	0.958	720	0.640	870	0.540
430	0.458	580	0.957	730	0.717	880	0.437
440	0.622	590	0.899	740	0.770	890	0.382
450	0.755	600	0.919	750	0.645	900	0.355
460	0.821	610	0.920	760	0.472	910	0.290
						920	0.216

posed of a single glass filter component combined with evaporated multilayers (Dobrowolski, 1970). They achieved a somewhat better fit to the desired spectral energy distribution, but the long-term stability of their spectral transmittance is not as reliable.

The filter position is such that it is protected from the light source by the shutter, except during actual exposure, and hence is not heated by radiation which could cause a change in filter transmittance.

The filter holder has provision for the insertion of a color filter, such as a Wratten 12, for situations where data are sought for a film-filter combination.

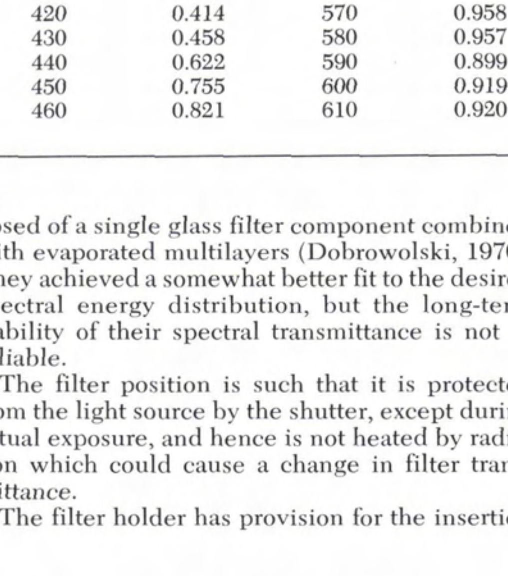

FIG. 3. Relative energy distributions of standard air photo daylight and the results obtained with a 2856 K source and three glass filters.

To maintain the daylight energy distribution of light emerging from the filter, the light is directed upward to the film by a totally reflecting prism of borosilicate crown glass rather than by a mirror which would have some absorption and might vary its reflectivity with age.

SHUTTER

The shutter is an extreme type of pendulum or gravity driven sector. It is shown passing through its open position in Figure 2, with the aperature and the off-center weight both directly below the axis of rotation. In use, the shutter is released from a position with the aperture and weight slightly (10°) to one side of straight up. It swings through the position shown and on through almost a full turn, being caught slightly further (about 17°) to the other side of straight up. The shutter is re-cocked by moving it through the straight up position to its starting point. Release, catching, and re-cocking mechanisms, not illustrated, are controlled mechanically by a single knob visible in Figure 1. The exposure time (speed) produced by this type of shutter depends on its dimensions and materials. It can be calculated in the design stage using the fact that the kinetic energy of rotation of the shutter, when the weight is at its lowest position, will be almost equal to the potential energy of the weight at its highest position.

The shutter does not tend to slow down with age as does a spring driven shutter. It also avoids the often unrecognized uncertainties of a shutter driven by a synchronous electric motor. Such shutters sometimes hunt about the central phase-locked position due to varying mechanical loads or to static imbalance. They may also fail to pull in to synchronization and may then run at a lower speed as an induction motor. Neither condition gives any obvious indication of failure.

The gravity driven sector shutter can, of course, be slowed down by increasing bearing friction or some other accidental drag, but before such slowing has any significant effect on exposure time it will cause the shutter to fail to reach its stopping catch position. Then it swings freely back and forth, eventually coming to rest in the open position, an obvious and complete failure. This qualitative statement of fail-safe operation can be readily confirmed quantitatively. A shutter released at 10° off center typically swings to 14.5° off center on the other side. The potential energy loss for this condition is given by

$$\frac{(1 + \cos 10°) - (1 + \cos 14.5°)}{(1 + \cos 10°)} \times 100$$
$$= 0.84 \text{ percent.}$$

The loss at the catch position is a further 0.60 percent. Thus, if increasing friction causes it to just reach the 17° catch instead of the normal 14.5° position, the 0.60 percent energy loss implies at worst a 0.30 percent speed loss and hence an increase in log exposure of 0.001—an insignificant change. Any further friction will cause complete failure.

This free swinging failure also may occur if the sensitometer is not reasonably level or if it is not firmly enough supported and can move or rock when the shutter operates.

The shutter has a nominal angular velocity of 1180°/s. An aperture of 19.7° (1.99 inch at 5 13/16 inch radius) was used to give an effective exposure time of 1/60 s in some early instruments, but all now use 9.85° to give 1/120 s in keeping with standards requiring less than 1/100 s to minimize reciprocity failure effects. These shutter speeds were chosen to pass either one or two complete cycles of the 120 hertz ripple occurring in the output of a tungsten lamp operating on 60 hertz alternating current, so that the mean lamp intensity during the exposure is the same as the long term mean determined in conventional photometry.

ELECTRICAL SUPPLY

The sensitometer requires auxiliary electrical equipment such as shown beside it in Figure 1 to operate the lamp at the voltage at which it was calibrated.

Control of lamp voltage rather than lamp current was chosen because voltage is the more sensitive indicator of light output. Light output is proportional to voltage raised to the power 3.38 and to current raised to the power 6.25 (General Electric, 1956). Consequently, a 0.5 percent error in voltage would cause a 1.7 percent error in light output whereas a 0.5 percent error in current would cause a 3.2 percent error in light output. The possibility of voltage errors due to lead and contact resistances is minimized as far as is practical by running separate voltage leads from the lamp socket to the voltmeter. Lamp socket and lamp base are cleaned whenever a sensitometer is calibrated. Trouble with variation of lamp socket resistance or internal lamp lead resistance has not been encountered in practice. The reference sensitometer at NRC has both a voltmeter and an ammeter.

For the typical sensitometer an A.C. voltage regulator has been used to provide 120 volts at 60 hertz, independent of power line fluctuations, for a variable auto-transformer which can be adjusted to provide the calibrated voltage. A voltmeter with a real maintained accuracy of 0.5 percent is used to read the voltage on the lamp. Since some common A.C. voltage regulators produced distorted wave forms, it is necessary that this voltmeter indicate true r.m.s. volts.

These electrical auxiliaries, their use and their misuse, have been the chief source of inaccuracies in exposure. Operator errors have sometimes caused large departures from calibrated values.

The procurement of suitable meters becomes increasingly difficult. Analog dynamometer voltmeters 20 years old still have the required accuracy, but comparable new meters, if available, are unreasonably expensive when considered as part of the system. Analog moving-iron meters, the recent solution, are a marginally satisfactory compromise on accuracy, stability, and cost. Considering the modern digital meters, it is found that relatively few read true r.m.s. volts and of these only an expensive few claim adequate accuracy. Even these do not claim to maintain this accuracy for more than a year. This compares unfavorably with the several years otherwise now found acceptable as a recalibration interval for the sensitometer.

The possibility of procuring a regulated adjustable direct current power supply, plus a direct current voltmeter, has been examined from time to time but is not yet attractive. Such a system, or even a completely pre-adjusted power supply, may become a practical solution in future.

Sensitometer Calibration and Verification

Prior to use, each sensitometer must be calibrated to determine the log exposure at the film plane for each step of the step tablet. This calibration to an absolute standard provides the user with the means for determining film speed as well as gradient. Originally it was considered desirable to recalibrate the sensitometers annually but this was found to be time consuming, expensive, and involved risks of shipping damage. A simpler verification procedure has been developed. The steps involved in these two procedures are outlined below.

CALIBRATION

Calibration of a sensitometer involves the following steps:

- Check of lamp for uniformity of illumination
- Determination of lamp voltage for 2856 K
- Measurement of film plane illuminance without daylight filter or step tablet
- Spectrophotometry of daylight filter, calculation of accuracy of spectral energy distribution (Carman 1969), calculation of luminous transmittance
- Calibration of step tablet
- Timing of shutter
- Calculation of log exposure values for each step of tablet
- Photographic intercomparison check against a reference sensitometer.

VERIFICATION

In principle, it is possible to check a sensitometer photographically. A sensitometric curve from a test strip exposed on the sensitometer to be tested is compared with one from a reference sensitometer. Film, development, and all other conditions affecting image density must be the same.

Test strips can be cut from the same piece of film and can be developed together, but when the sensitometers being compared are far apart, the other conditions encountered during shipping and handling the film present serious problems. The verification procedure in use to minimize or at least identify shipping problems is as follows:

- Cut three test strips from the same film.
- Expose #1 on reference sensitometer.
- Pack all three in light tight envelopes and a thermally insulating box and send all three to owner of sensitometer to be tested.
- Sensitometer owner exposes strip #2 on his sensitometer and returns all three.
- Expose #3 on reference sensitometer.
- Develop three test strips together (long development with nitrogen burst agitation).
- Measure densities and plot sensitometric curves of density versus log exposure for all three strips.

If the sensitometer being tested has retained its calibration and if shipping effects have not caused problems, the three sensitometric curves should be practically coincident. If they do match within 0.05 log exposure units, the sensitometer's calibration is considered to remain valid. If #1 and #3 curves differ significantly from one another, effects have occurred in shipping and the test must be repeated. If #1 and #3 are reasonably close, but #2, from the test sensitometer, differs significantly, it is usually concluded that the calibration is invalid and the sensitometer should be recalibrated.

Sometimes it may be guessed that the difference arises from operator error, and the test is repeated after discussion with the owner. This possibility of detecting and encouraging correction of operator error is an incidental but very important advantage of verification compared to recalibration.

This verification procedure has been found to work best when outdoor temperatures are moderate in spring and fall. Problems due to shipping film in hot summer weather were expected, but problems in cold weather were a surprise. Their occurrence, as evidenced by density differences between exposure #1 and #3, is clearly established but no detailed explanation has been attempted.

USES OF SENSITOMETRIC CONTROL OF AERIAL PHOTOGRAPHY IN CANADA

Through the requirements of the Specifications for Aerial Survey Photography issued by the I.C.A.S., the use of the NRC Sensitometer and sensitometric control of aerial photography has become commonplace in Canada.

The routine printing of calibrated sensitometric exposures on survey rolls was introduced primarily to provide a means of identifying troubles that *had* occurred. For example, if negatives lacked density, film speed and average gradient could be measured to see if film speed and development were as expected. If they were, camera exposure was indicated as the problem.

The sensitometers have also proved useful for several other purposes:

TESTS OF FILM STOCKS

Sensitometric tests of film stocks are made to establish actual film speed(s) and average gradient(s) prior to operational use of the film. This is particularly important where films are kept in long-term cold storage.

This type of monitoring has shown that, although the overall sensitivity of Kodak Aerographic Infrared film decreases steadily with time, the infrared sensitivity remains nearly constant relative to the overall sensitivity (Fleming, 1980a).

Similarly, differences in speed or contrast between different film batches are detected and compensated in exposure and processing.

CONTROLLING COLOR BALANCE IN COLOR INFRARED FILM

As a result of standard, well controlled processing, and calibrated sensitometry, it has been possible to define the IR-balance of infrared color films, show how this balance differs with different film batches, and, most importantly, devise means of controlling the balance so that uniform results can be obtained regardless of film batch or flight altitude (Fleming, 1978; Fleming, 1980b).

EFFECT OF AMBIENT CONDITIONS ON FILM SENSITIVITY

Sensitometric tests carried out under controlled conditions of elevated temperature have provided useful information on the effects of various departures from optimum conditions and on techniques for minimizing adverse effects (Carman, 1980).

Statistical Studies

Data from films processed by a single organization have been used to establish the consistency of sensitometric characteristics being achieved (Fleming, 1976). Furthermore, the results from many organizations have been compared for differences in speed and gradient as results of different processing techniques.

Uniformity of Processing

Sensitometric exposures throughout the length of a roll were used to establish the improvement in processing uniformity achieved with continuous processing as contrasted to that achieved by rewind methods (Walker, 1967).

Acknowledgments

The development and use of sensitometers for control of aerial photography was inspired and encouraged by the Joint RCAF-NRC Photographic Research Committee and its successor, the NRC Associate Committee on Photographic Research. The present sensitometer was drawn and from time to time revised by D. Torney, H. Purdie, and B. Wheeler and the prototype was built in the Physics Divisional Workshop by M. Mercier and G. May.

The original three-component "daylight" filters to H. Wright's (1969) design were made by the Physics Division's Optical Components Laboratory. J. Fleming of Energy, Mines and Resources later arranged for the commercial procurement of twelve. The glass plus multilayer filters to J. A. Dobrowolski's (1970) design were made with his facilities by A. Waldorf on glass from the Optical Components Laboratory.

Calibrations and verifications involve many Optics Section facilities and personnel, principally R. Fink.

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* Copies of these reports may be obtained from the Interdepartmental Committee of Air Surveys, Department of Energy, Mines and Resources, 615 Booth Street, Ottawa, Ontario, Canada K1A 0E9.

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