Photometric Calibration of the Surveyor Television System

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A complete prelaunch calibration was performed on each Surveyor television system to allow accurate reconstruction of the televised pictures. Photometric calibration data served to define system performance in terms of lunar luminance units, thereby allowing the television camera to be used in determining relative and absolute luminance values of selected portions of the lunar terrain. Development of such calibration data required the evaluation of a correction factor such that lunar performance could be predicted from measurements obtained with conventional light sources.

Introduction

THE Surveyor television system[1] is intended to provide photometric and photogrammetric information about the lunar terrain, to participate in scientific experiments, and to provide the visual feedback loop necessary to conduct the experiments. Therefore, its performance characteristics must be accurately known under all expected operating conditions. The main parameters of interest are light transfer characteristics, spatial frequency response, geometric linearity, polarimetric constants, and vidicon erasure characteristics. Accurate determination of camera-spacecraft orientation is assured by performing the calibration with the camera mounted and aligned in the flight-ready spacecraft.

The accuracy with which such lunar properties as albedo, polarizations, spectral reflectance, and lunar photometric functions can be determined is dependent upon the accuracy with which the prelaunch calibration was performed. The photometric calibration data allow the televised picture to be reconstructed by digital computer techniques on an element-by-element basis. These data also provide camera characteristic plots for use during real-time mission operations. From these data, estimates of iris settings or exposure durations can be made for given sun angles or camera viewing positions. Recommendations as to nonstandard operating procedures take into account such calibrations. Portions of the recorded calibrations are also used to calibrate the Ground Data Handling System from its input at the Goldstone tracking station to its output at the Pasadena operations control center, during each operating day of an active mission.

The television camera (Fig. 1) employs a vidicon sensor operated in either of two slow-scan modes. The 600-line scan mode provides excellent picture quality at the cost of greater signal bandwidth. It requires 3.6 sec for a full-frame cycle, which includes 1 sec for vidicon readout, 0.2 sec for frame identification data, and the remaining 2.4 sec to assure complete vidicon erasure. The information is contained in a 220-kHz baseband. The 200-line mode is available in the event that either the high-power transmitter or high-gain antenna is not operable. It requires 60.8 sec for a full-frame cycle of which 20 sec are allocated to vidicon readout. The information baseband is restricted to 1.2 kHz.

The camera used a focal-plane shutter to prevent picture blur due to motion of the optics and to protect the vidicon from viewing the sun directly. By means of earth command, three exposure modes are available: shuttered, open-shutter, and integrate exposure mode. The exposure modes, coupled with commandable iris control, allow the camera to accommodate scene brightness levels from 0.008 to 10,000 ft-lamberts. A variable focal-length lens permits narrow-and wide-angle viewing. A movable mirror allows azimuth and elevation viewing over the full 360° of azimuth, and from +40° to −60° above and below the camera Z axis. An azimuth step size of ±3.0° and an elevation step size of ±2.48° are provided. The composite video signal contains the necessary synchronization, blanking, and frame identification signals. Frame identification signals contain optical, electronic, and position data required to describe the relative location and optical characteristics of the televised scene.

The details of the rigorous prelaunch calibration effort and the results obtained are the subjects of the remainder of the paper.

Methodology

The camera's photometric characteristics had to be determined under simulated lunar conditions. This represented a departure from conventional practices where light-

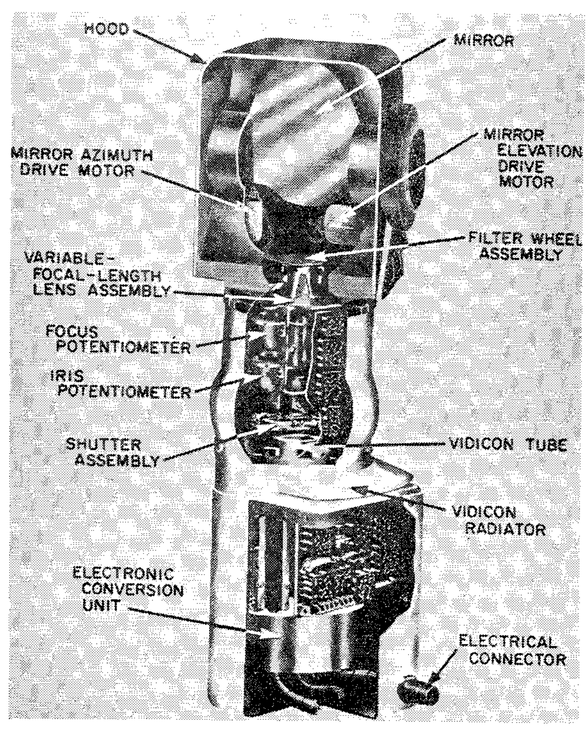

Fig. 1 Cutaway view of camera.

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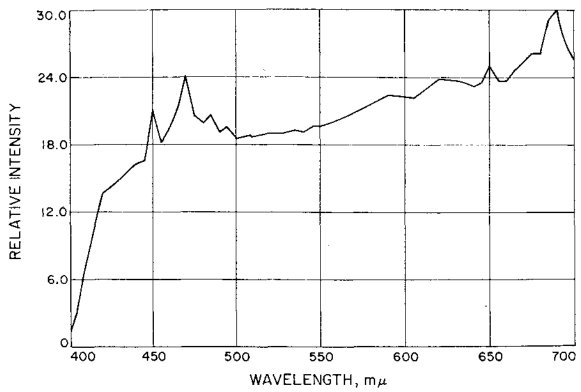

Fig. 2 Spectrum of surveyor TV calibration light source.

transfer characteristics are defined in terms of a standard luminous source. Moreover, the lunar emission spectrum covered a large brightness range. Since the spectral content of our calibration light source did not match the lunar scenes exactly, a source-lunar luminance correction factor was then computed to account for the differences.

Photometric calibration included all measurements pertaining to the light-transfer characteristics of the television camera system, including 600- and 200-line scan modes, the presence of polarizing or colored filters, iris repeatability and exposure reciprocity, vidicon shading characteristics on a line and frame basis, dark current buildup in both scan modes of all iris aperture positions, and normal and open-shutter modes. The light-transfer characteristics were measured by applying a known input function simulating the lunar scene and measuring the output response, which was the corresponding frequency modulation of the spacecraft transmitter carrier. The resultant system transfer function defined carrier deviation as a function of lunar scene luminance, thereby incorporating elements of both the television camera and the rf subsystem.

The source-lunar luminance correction factor is derived in photovisual units [see the Appendix, Eq. (A8)]. It requires the spectral distributions or responses of all elements of the calibration setup. Of these, the lunar reflection spectral distribution is the most difficult to obtain. It is best approximated by a point-by-point multiplication of the solar emission curve (Johnson curve) and the lunar reflectance curve. Because of the lack of color detail on the lunar surface, the lunar reflection spectral curve can be applied to most areas of the lunar surface.[2] The spectral characteristics of the vidicon/-optics assembly were measured at the Jet Propulsion Laboratory (JPL) prior to assembly in the camera. Also, the spectral energy contents of the calibration and reference light sources were verified by means of spectroradiometer prior to each spacecraft calibration.

The job of obtaining photometric calibration data can be divided into two tasks: photometry (alignment and operation of the light sources and periodic equipment checks) and electronic-photographic data recording (preparation of properly annotated video tape and collection of real-time "A" scope polaroid picture data). The light-transfer characteristics in both scan modes were obtained by setting a fixed luminance level at the calibration light source (CLS) and cycling through all camera iris positions. At each iris position, several video frames were recorded on videotape, and at least one "A" scope polaroid picture was obtained. A voice track, NASA time-code track, and a 60-Hz reference oscillator track also were recorded for identification and accurate playback. This procedure was repeated at each desired luminance level. Real-time measurements were made on "A" scope polaroid pictures representing single lines of video. The scan lines selected contained reseau marks to permit identification of the same scan line in each of the polaroid pictures. System response was always measured at the center of each scan line, thereby eliminating any error due to vidicon shading. Variations in data due to incomplete erasure were avoided by recording the first frame after exposure and by allowing adequate erasure time after completion of a series of exposures at one luminance level.

The determination of light-transfer characteristics in the presence of polarizing or colored filters follows the same procedure in terms of calibration and data reduction. It is necessary to include the measured cross-spectral response of the camera and filter in the final data tabulation.

In the integration-exposure-mode calibration, which defined the time rate of dark-current buildup, the CLS was reduced to near-zero luminance, the camera was covered with a black cloth and, with the shutter open, scanning was inhibited for a predetermined time. Then scanning was enabled and the resulting dark-current level was recorded. The procedure was repeated for several different time durations up to 20 min in length. Departures from exposure reciprocity are frequently encountered in imaging systems for either very low or very high input brightness levels. Such reciprocity failure indicates that the photoelectric reaction inherent in the camera is not totally defined by just the total input energy. Measurement of exposure reciprocity began by selecting a constant value of output voltage and adjusting the CLS brightness to attain the same video output voltage at various commanded iris positions. This is equivalent to evaluating the change in lens aperture brought about by a change in scene brightness, with the image brightness held constant.

The iris repeatability calibration evaluates variations from commanded aperture positions in terms of signal level output for a given scene brightness, as well as variations in iris potentiometer settings resulting in variations in aperture readings at commanded positions. The magnitudes of the variations are indicative of the mechanical tolerances in the lens-iris subassembly. Iris repeatability was evaluated by selecting a particular iris setting, say f/8, and then commanding the iris to step several times to f/5.6 and f/16 and then return to f/8, where variations in camera signal output and iris position readings were noted. At each setting for which repeatability was evaluated, the CLS was set to yield a video output signal that was approximately in the middle of the light-transfer characteristic. Results were graphed.

Calibration Equipment

Target slides were used to aid in alignment during the photometric calibration. They serve as input functions during other calibration activities such as in determining modulation transfer functions, or geometric distortions.

The CLS utilized xenon lamps in conjunction with an integrating hemisphere. Resulting performance included a measured field uniformity of 3%, with luminance continuously adjustable from 4 to 2500 ft-lamberts. Spectral shifts were avoided by incorporating an adjustable iris for luminance level control. Alignment slides were mounted in the CLS for source-camera alignment. A diffusing plastic screen provided the flatly illuminated surface used in simulating various levels of input illumination. The spectral distribution of the CLS is shown in Fig. 2. The spectral content is reasonably constant over the visual response region, as desired.

The measuring photometers used were Gamma Scientific Model 700 photometer (hereinafter designated MP) and Model 2000 telephotometer (hereinafter designated TP). In a working situation, readings were taken with the MP, with periodic calibration checks made against the readings obtained with the TP. The TP was in turn calibrated against the Gamma Scientific Model 200 and Model 220 standard light sources.

Since the television system output function is an FM carrier, the response recordings are prepared in the rf domain. The recording/playback configuration and equipment are depicted by a block diagram (Fig. 3). The predetection signal

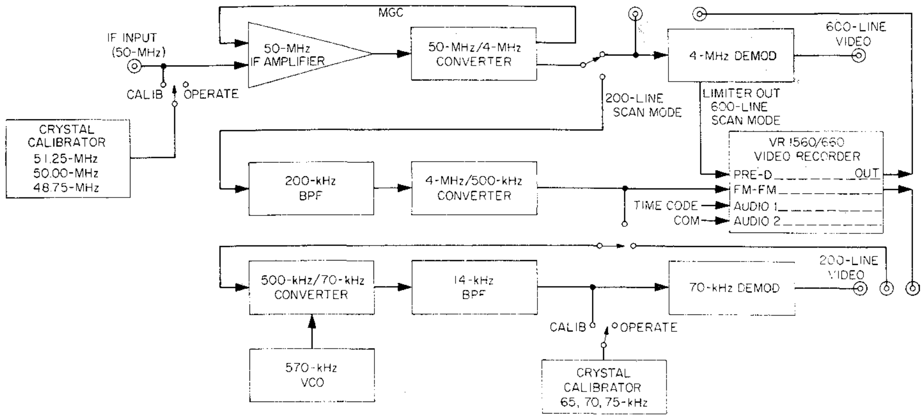

Fig. 3 Video recording system block diagram.

was recorded, providing calibration information free from unknown factors and nonlinearities associated with the normal video test equipment. The tape recorder consisted of an Ampex VR 1560 rotating-head, helical-scan machine, modified to a VR-660 configuration. Other modifications allow direct-level recording as well as recorder-servo control when applying nonstandard (slow-scan) video information. Video information was obtained from the first IF stage of the receiver in the system test equipment assembly (STEA), at which point the carrier frequency is 50 MHz. This 50-MHz signal was amplified and then converted to 4 MHz. In the 600-line scan mode, this 4-MHz signal was hard-limited and applied to the predetection input (direct record) of the recorder. In the 200-line scan mode, the 4-MHz signal was further converted to 500 kHz and then applied FM-FM to the recording machine.

The 600-line scan mode playback was accomplished by demodulating the 4-MHz carrier through a carefully calibrated pulse-averaging-type demodulator to obtain the baseband video signal. The 200-line scan mode playback required another frequency conversion to 70 kHz for demodulation through an existing 70-kHz demodulator. Included in the recording equipment was a selectable set of crystal calibration frequencies that could be used to allow the vertical deflection axis of a recording "A" scope to read in frequency units. This simplified and improved the accuracy of the "A" scope measurement of carrier deviation.

Instrumentation

The CLS was located 6 ft ± 0.5 in. from the camera such that its axis lies in the tilt plane of the camera. The camera mirror was set to an appropriate azimuth and elevation setting, and the axis of the CLS was aligned to the optical axis of the camera. Final alignment was achieved by using an alignment target, taking test TV pictures, and adjusting the CLS so that the alignment target fills the camera field of view (a primary requirement) as observed on STEA monitor.

The TP was located so as to enable the operator to measure both the CLS and the standard light sources. The distance from either of these sources is unimportant, but it is important that the TP line of sight be normal to a source's luminous surface. The MP was near the CLS as dictated by the fiber optics coupling probe.

The CLS and photometers were periodically calibrated to a standard light source to correct for photometer drift as follows. The TP was used as a transfer photometer and, in effect, allowed the MP to be indirectly calibrated against the standard light source. In practice, the standard source was measured with the TP, whose scale was set to read 100 ft-lamberts. The TP was then pointed at the center of the diffusing surface of the CLS, and the latter's luminance was adjusted to cause the TP to read 100 ft-lamberts, as with the standard light source. The MP was then adjusted to read 100 ft-lamberts with the fiber optics probe in its working position. The CLS's diffuser was slightly darker at the edge where the fiber optics probe was located. Therefore, by setting the MP to indicate the diffuser center luminance, a more accurate measurement of camera input luminance was obtained.

Data Reduction

To determine the photometric characteristics of the television system, its response was measured to a known CLS luminance, and then the measured response was related to an equivalent lunar luminance. This procedure defined the light-transfer characteristics in terms of frequency deviation as a function of lunar luminance, as shown in Fig. 4.

For mission operations usage, a portion of the recorded calibration data was reduced by manual techniques. The remaining data were reduced by digital computer for use in post-mission data reduction and correction.[3] The techniques were similar and are perhaps better understood by considering the manual reduction procedures. The frequency deviation resulting from a known luminance input was measured from sync pulse back porch, and later scaled to represent deviation from carrier for user convenience. A direct measurement of frequency deviation was possible, since known calibration frequencies were always superimposed on the "A" scope polaroids. Since frequency deviations were measured relative to carrier, the final measurement tabulation listed positive and negative frequency deviations, from carrier, vs CLS brightness. To scale the CLS brightness reading to an equivalent lunar brightness, a meter correction factor was applied and the resulting corrected brightness was scaled by a source-lunar luminance correction factor. The meter correction factor was obtained from a measured curve of the linearity of the MP; it varied with meter deflection and selected meter range.

The error from the standard light source was ±2%. The error from transferring the 100 ft-lambert reading by means of the TP was ~0.1%. It then seems reasonable to assume that the absolute photometric error did not exceed ±2% at the 100 ft-lambert level for the most measurements. The error in determining photometer linearity was less than 1%. The photometric setting error over the range of luminance values used should have been less than ±3% in most cases.

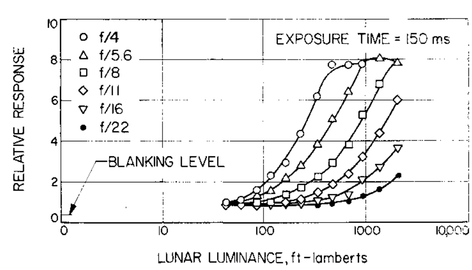

Fig. 4 Light-transfer characteristics.

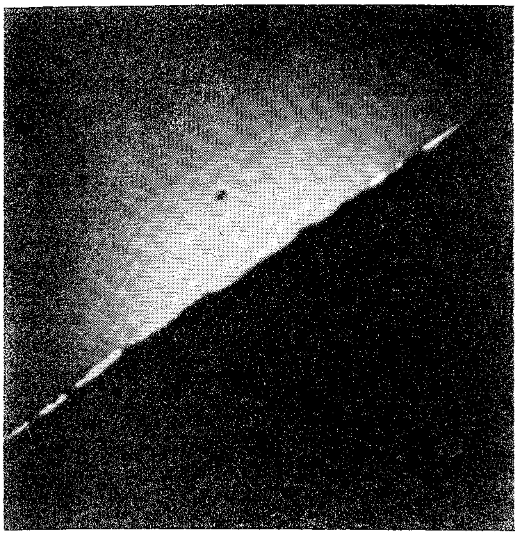

Fig. 5 Surveyor solar corona picture.

Mission Applications

Polarization characteristics of selected portions of the lunar landscape were analyzed during later missions in which the TV camera was equipped with polarizing filters to reveal the chemical composition of lunar soil. Earlier Surveyor television cameras were fitted with color filters to reveal the color-characteristics of the lunar landscape. The accuracy with which either of these experiments could reveal the true nature of the lunar terrain depended upon the precision with which the prelaunch television system characteristics were defined.

Television pictures of solar corona, Fig. 5, obtained during lunar sunset are currently being analyzed to determine the intensity of both K and F corona, and perhaps add to the knowledge of the interplanetary medium and the solar wind. Photometric accuracy is a prime necessity for these measurements. Star-field pictures obtained during the lunar night provide geometric calibration of the optical/electronic imaging system to reveal any changes that may have occurred. Estimates of stellar magnitudes are provided from photometric calibration data. A technique developed at JPL during the Ranger program for generating contour maps from terrain photographic images is being considered for certain Surveyor frames. Although this technique does possess some theoretical limitations, it can serve as an interpretative aid.

Figures 6 and 7 illustrate one step in the processing of Surveyor pictures to achieve the needed accurate reproduction of photometry. Figure 6 shows the results of correction for photometric error introduced by the TV system. Before correction the delineated areas appear to be of considerably different luminance; after correction, they are of equal luminance. Figure 7 is a reproduction of computer print-out data representing part of the areas delineated in Fig. 6. Before correction, on television line 151, picture elements 183 and 547 have relative intensity values of 40 and 46, respectively; after correction, they are both 47. The print-out before correction gives relative amplitudes on a scale of 0 to 63. In the correction process the computer introduces the transfer characteristics for the system for each picture element (i.e., including filters, aperture, etc.). The corrected array also is on a scale of 0 to 63. In the example the scale is linear, with 63 representing black and 0 representing 3000 ft-lamberts. Therefore, 47 units is known to represent 760 ft-lamberts.

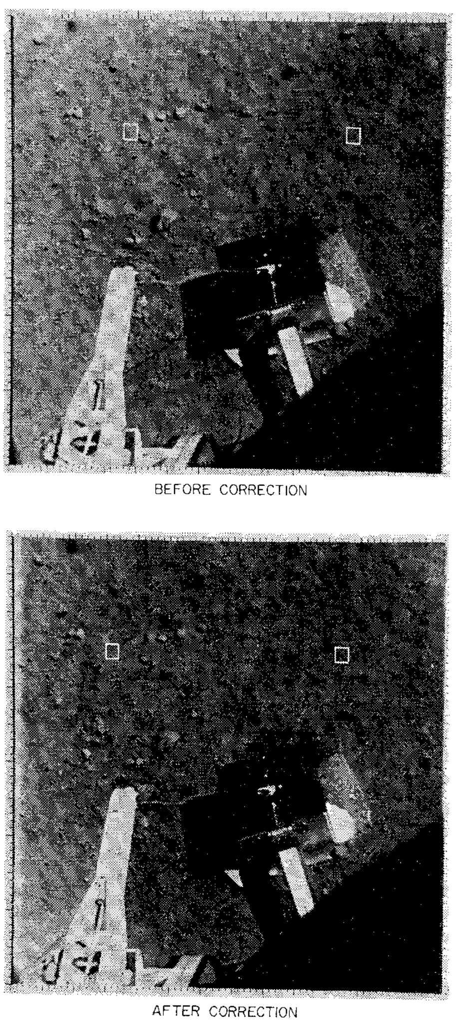

Fig. 6 Surveyor science photometric correction.

Conclusions

Photometric calibration of a television camera requires the recording of photometric response at every picture element location within the camera image plane. And, since the calibration light source has a spectral distribution that is significantly different from the lunar spectral distribution, a correction factor is required. The spectral characteristics of each element of the calibration setup must be accurately known. Videotape recording of the predetection FM television signal provides the necessary storage volume. The fidelity of the calibration data is preserved by recording the predetection signal, thereby eliminating nonlinearities usually found in video test equipment. Crystal calibration frequencies provide known references against which FM carrier deviations can be measured.

BEFORE CORRECTION

SAMP	183	184	185	186	547	548	549	550
LINE								
151	40	37	36	36	46	45	46	47
152	39	38	37	36	46	46	45	46
153	36	37	37	37	46	45	45	46
154	34	37	37	36	46	45	45	46

AFTER CORRECTION

SAMP	183	184	185	186	547	548	549	550
LINE								
151	47	44	44	44	47	46	47	48
152	46	45	44	44	47	47	46	47
153	44	44	44	44	47	46	46	47
154	42	44	44	44	47	46	46	47

Fig. 7 Luminance plot of photometric correction.

The error of the photometric calibration is about ±3% over a range of luminance levels from 10 to 2500 ft-lamberts. The predominant error sources are contributed by the 100 ft-lambert standard source and the photometer nonlinearity. Field uniformity of the calibration light source was measured prior to and during the calibration and was effectively removed as an error source in the final data reduction.

The major source of error in the television system calibration is the assumed lunar spectral distribution; additional errors arise from variations in the optics or vidicon spectral characteristics with time. Electronic gain changes do not contribute significant errors due to the large amounts of stabilizing feedback employed in their design.

Appendix: Derivation of Source-Lunar Luminance Correction Factor

We wish to define a factor such that the measured calibration source brightness can be scaled to an equivalent lunar brightness for the same camera output.

The measured calibration source brightness B_s is the cross-spectral response of the calibration source $H(\lambda)$ and the measuring photometer $R(\lambda)$ (where λ is wavelength); i.e.,

$$B_s = \int_0^\infty k_1 R(\lambda) k_2 H(\lambda) d\lambda \qquad \text{(A1)}$$

where k_1 and k_2 are the photometer and calibration-source scale factors, respectively. We must simply determine k_1 and k_2.

Consider the use of a reference source having a brightness B_r of 100 ft-lamberts; that is,

$$B_r = \int_0^\infty I(\lambda) k_3 E(\lambda) d\lambda = 100 \text{ ft-lamberts (visual)} \qquad \text{(A2)}$$

where k_3 is the reference source scale factor and $I(\lambda)$ and $E(\lambda)$ are the spectral responses for the standard eye and the reference source, respectively.

We can use the reference source to calibrate the photometer, that is, to determine k_2. The photometer will real 100 ft-lamberts when

$$\int_0^\infty R(\lambda) k_3 E(\lambda) d\lambda = 100 \text{ ft-lamberts} = \int_0^\infty I(\lambda) k_3 E(\lambda) d\lambda \qquad \text{(A3)}$$

and

$$k_1 = \int_0^\infty I(\lambda) E(\lambda) d\lambda \Big/ \int_0^\infty E(\lambda) R(\lambda) d\lambda \qquad \text{(A4)}$$

Now to determine k_2, we require the camera output to be the same from the source as from the lunar scene. That is,

$$\int_0^\infty V(\lambda) k_2 H(\lambda) d\lambda = \int_0^\infty V(\lambda) k_4 S(\lambda) d\lambda \qquad \text{(A5)}$$

where k_4 is the scale factor for lunar spectral distribution, $V(\lambda)$ is the vidicon spectral response (including filters), and $S(\lambda)$ is the lunar reflection spectral distribution. Also, the visual lunar brightness is just

$$B_m = \int_0^\infty I(\lambda) k_4 S(\lambda) d\lambda \qquad \text{(A6)}$$

which yields k_4. Substituting (A6) into (A5) and solving for k_2, we obtain

$$k_2 = \frac{B_m \int_0^\infty V(\lambda) S(\lambda) d\lambda}{\int_0^\infty V(\lambda) H(\lambda) d\lambda \cdot \int_0^\infty I(\lambda) S(\lambda) d\lambda} \qquad \text{(A7)}$$

The required source-lunar luminance correction factor is

$$\frac{B_s}{B_m} = \frac{\int_0^\infty I(\lambda) E(\lambda) d\lambda \cdot \int_0^\infty V(\lambda) S(\lambda) d\lambda \cdot \int_0^\infty R(\lambda) H(\lambda) d\lambda}{\int_0^\infty E(\lambda) R(\lambda) d\lambda \cdot \int_0^\infty V(\lambda) H(\lambda) d\lambda \cdot \int_0^\infty I(\lambda) S(\lambda) d\lambda} \qquad \text{(A8)}$$

Once this factor is determined for a particular system, readings of source luminance can be divided by it to obtain equivalent values of lunar luminance.

References

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