Automated Measurements of Atmospheric Visibility

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ABSTRACT

The concept of using a solid-state, linear-array imaging device coupled with computerized scene analysis and display to measure daytime atmospheric visibility is described. Computer software is implemented for routine conversion of observed target and sky radiances into measurements of horizon contrast, visual range, target color impairment, and target modulation depth, i.e., target texture and clarity. An assembled, working instrument has been applied to field measurements. Several examples of field measurements are presented. The instrument is fully automated, and is available for visibility research; its applicability to routine visibility monitoring and as an operational tool for aircraft operations is explored.

1. Introduction

A new technology for automated monitoring of atmospheric visibility has been implemented and tested by SRI International under funding and support from the Electric Power Research Institute (EPRI). A prototype instrument called the Automated Telephotometer has been assembled and calibrated, and its performance evaluated in the field. The instrument is designed to simulate and quantify the process by which a human observer determines prevailing visibility (Viezee and Evans, 1980). Thus far, the prototype automated telephotometer has been applied primarily to monitoring relatively high (>10 miles) visibilities for air quality assessment in pristine areas (Evans and Viezee, 1982). However, experience with low-visibility situations suggests that the technique can be successfully applied to airport visibility monitoring. This paper describes the prototype instrument, and presents examples of its data-analysis capabilities.

2. Description of prototype instrument

a. Block diagram

Fig. 1 shows a block diagram of the automated telephotometer. Two essentially independent units are provided; the primary unit is intended for data acquisition and real-time automated analysis; the other unit is used to perform in-depth data analyses and to examine scene images. Each unit is constructed around a Z-80 microcomputer controlling an industry-standard S-100 bus. Each computer is fitted with 32 K bytes of random-access memory (RAM), a single 8-inch floppy disk drive, and small sections of read-only memory (ROM). This dual S-100 bus approach provides flexibility as well as the reliability associated with slightly redundant, but relatively inexpensive equipment. With only minor rearrangement of the plug-in cards, either computer can perform most of the functions normally assigned to the other. Implementation of a spectral (color) measuring capability requires only substitution of a color camera head with filter wheel (heavily shaded block in Fig. 1), its interface card (lightly shaded block), and slightly expanded operating software.

b. Sensor

The sensor is a Reticon Model LC100 solid-state line scan camera, fitted with an RL256EC detector element that provides a linear array of 256 silicon photodiodes, 0.001-inch wide, and with 0.002 inch center-to-center spacing along the length of the array. The camera housing, which is 2.8 × 4 × 6 inches in size, contains four circuit cards. Clock signals provided by the computer cause the camera circuits to scan (i.e., sequentially sample) the 256 photodiodes, condition the output signal into a stepped waveform using "sample-and-hold" techniques, and provide output amplification capable of driving a long transmission cable to the computer. For most tests made to date, the camera is fitted with a 50-mm f/1.4, C-mount lens that, when focused at infinity, provides a fan-shaped field of view approximately 15° high by 0.06° (1.03 milliradian) wide.

c. Sensor rotator assembly

The rotator assembly provides a compact, all-weather means of positioning the Reticon camera through 360 degrees of azimuth in 4000 repeatable steps (1.57 milliradian per step). The basic mechanical assembly is a readily available commercial unit.

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intended for rotating medium-sized TV and communication antennas. The basic unit has been modified to adapt it to precision computer-controlled positioning of the camera. In this modification, the standard drive motor and some of the associated gearing have been replaced by a stepping motor that can be controlled by the system computer at a rate of approximately 50 steps per second. In addition, a helical spring and multiconductor cable assembly has been added to permit acquiring data from the Reticon without the need for either slip rings or external cable loops.

d. Data acquisition computer

The data acquisition computer is a small, easily portable unit that provides power and space for eight S-100 cards, including a Z-80 CPU card. Aside from a teletypewriter console, its only external controls are an “On/Off” power switch, and a “Reset” pushbutton. While the unit is a complete, general-purpose computer capable of signal analysis and driving a wide variety of peripheral devices, its principal function is to program the Reticon camera and associated rotator to acquire brightness profiles and to store these profiles as dated files on its mass storage medium, an 8-inch flexible magnetic disk (240 K bytes).

e. Data analysis unit

The principal intended function of the analysis unit with its analysis computer (Fig. 1) is to provide a means for in-depth data reduction and interpretation of the brightness profiles collected by the telephotometer—an independent function that can proceed at any desired pace without interrupting the acquisition tasks that are being performed automatically and routinely by the telephotometer sensor system. The main function provided by the analysis computer, which is not (at least partially) available in the acquisition computer, is a 256 × 256 × 8 bit image storage memory and associated television monitor used for display. With this function, a long series of successive profiles obtained by the sensor can be assembled into intensity-modulated, two-dimensional images of selected portions of the panoramic scene. If desired, these images can be photographed for archival storage and post-analysis.

3. Current configuration

Fig. 2 shows the current configuration of the prototype instrument used for automated data acquisition. It consists of a small, slow-scan video camera with a precision rotary mount (Figs. 2a,b) remotely controlled by a micro-computer (acquisition computer in Fig. 2c). The acquired digital data are recorded on disk, and are analyzed in real-time with hard copy printout; they can also be used to generate images of the viewed scenes. When programmed for automated, routine monitoring of visual range and/or prevailing visibility, the sensor is fitted with a photopic filter (Fig. 2a) to obtain scene-brightness measurements within the spectral response of the human visual system (Vieze and Evans, 1980). The color camera (Fig. 2b) quantifies chromatic aspects of the visibility scene. It consists of a Reticon solid-state line-scan camera, and includes a before-the-lens filter wheel assembly. Ahead of the filter system is a removable, cylindrical light trap which effectively reduces light entering the system from outside the target area (flare light). The wheel has four filter stations, permitting operation in either of two generic modes of color analysis: a mode using four narrow-band filters to sample the spectral signature at four discrete points, or a mode using three broadband filters viewing in slightly overlapping portions of the spectrum. Currently, the “three-color broadband” approach is used, which approximates the CIE \( \bar{x} \), \( \bar{y} \), and \( z \) tristimulus distribution functions for a 2° observer (Evans and Vieze, 1982). The color camera uses the same rotator assembly as does the photopic camera, and, therefore, scans in azimuth at the same increment of 1.57 mrad per step. The average time required for a complete cycle through three or four filters is approximately 1 second.

4. Automated data acquisition and analysis

Software has been implemented to control the photopic camera through a programmed clock-initiated data acquisition cycle, viewing selected azimuthal sectors within the 360° horizon circle, and then storing the target images in digital form on magnetic diskettes. A compatible set of programs automatically analyzes the digital sensor records to provide numerical measures of horizon contrast, visual range, and prevailing visibility. Also indices are automatically generated that quantify the clarity of ter-
rain features derived from analysis of the fine-scale brightness contrast structure of the terrain. These indices disclose information about visibility when the horizon contrast method is ambiguous or the horizon is obscured.

The stored digital brightness data can be replayed in the form of gray-scale images on a standard TV monitor, for visual inspection and post-analysis of the recorded visibility conditions.

a. High-visibility environment

Fig. 3 illustrates a sample of data output from the automated telephotometer when the system was field-tested in a high-visibility (>10 miles) environment at a site near Flagstaff, Arizona, during October 1980. Fig. 3b shows a picture-image of a distant visibility target (48 miles from the location of the sensor) generated by the scanning camera and displayed on the
video monitor. A single, 250-pixel profile of brightness data along a 15° vertical field-of-view is shown in Fig. 3a. Various features pertinent to visibility monitoring are apparent in the profile data. For example:

- The horizon is clearly identified, and its clarity can be quantified by examining brightness gradients along the profile. The horizon is the point of largest gradient following the sky background.
- During atmospheric conditions when the natural horizon is obscured, visibility can be obtained by analyzing and quantifying the contrast structure of close-in terrain targets.

b. Horizon contrast

Fig. 4 shows an example of on-site, real-time printout from the data-analysis program that computes (by spatial integration of the measured data) apparent horizon contrast and visual range. Figure 4a is a matrix of brightness measurements (eight successive profiles) across Egloffstein Butte (see Fig. 3b). In each profile, the numbers represent the brightness count within a 1 milliradian angular view corrected for sensor dark current and for spatial variations in the individual diode response of the sensor diode array. Profile data are recorded at azimuthal steps of about 1.5 milliradian. Brightness gradients along each profile (Fig. 4b) are computed going from the background sky to the terrain.
below the horizon. The largest negative number identifies the horizon location.

This negative number is associated with two profile elements in Fig. 4a. Apparent contrast (Fig. 4c) is computed by taking the difference between the brightness count above and below these two profile elements (horizon location), and then dividing by an average count in the background sky. Using the average of the eight horizon-contrast values, visual range is obtained from Koschmieder’s Law for a nonreflecting (black) target. For the data sample of Fig. 4, the visual range is about 99 miles.

c. Terrain-contrast structure

If the analysis routine used to compute horizon contrast finds large gradients in the background sky above the horizon, cloud cover is the probable cause. If the maximum gradient is found below the normal horizon location, the horizon is considered to be obscured. In this case, a visibility index is obtained by analyzing contrast structure on the terrain below the horizon as follows:

- From eight successive vertical profiles, a matrix of brightness counts is generated for selected terrain below the horizon.
- The measured brightness counts are corrected for sensor dark current and for spatial variations in the relative response of the diode array.
- For each vertical profile, the brightness deviation of the profile elements from a five-point running mean is computed. This statistical high-pass filtering identifies fine-scale structure (high-frequency fluctuations) in the measurements.
- The pixel-by-pixel brightness deviations (high-frequency fluctuations) within successive increments of angular field-of-view (distance) are examined as a measure of terrain structure and detail.

Using the above procedure, an objective analysis rou-
tine was formulated and implemented into the automated telephotometer system. Hardcopy printout of the analysis results are shown in Fig. 5 for the visibility conditions that existed at 0900 MST 23 October in the direction of Eglffstein Butte, 48 miles from the field site (Fig. 3).

The matrix in the upper part of the figure is the measured brightness count (minus the sensor dark current) at 28 pixels for eight successive profiles between Eglffstein Butte at a distance of 48 miles to the railroad about 1 mile from the location of the sensor. The lower matrix represents brightness deviations from a five-point running mean. To aid in the interpretation, these data are grouped into arrays of 6 (profile-element brightness deviations) × 8 (profiles) that represent the far terrain at an average distance of 38 miles, the intermediate terrain at 20 miles, and the close-in terrain at 10 miles.

The information related to terrain texture or structure for each distance-dependent segment is summarized at the bottom of the figure by indicating the average brightness, the rms standard deviation and the rms deviation normalized to the mean brightness. This latter index is quite similar to the concept of modulation depth discussed by Henry et al. (1981) in connection with the quantitative analysis of visible scene-texture from photographic slides.

d. Low-visibility environment

Fig. 6 shows a time series of gray-scale images from measurements obtained by the scanning telephotometer during a period of early morning fog. The seven images portray a situation of dissipating fog, from dense conditions near 0900 and 1000 to clear conditions by 1500 LST. The high-rise building which was monitored is about 1 mile from the location of SRI International where the system was operated. Fig. 7 illustrates three samples of printout from the analysis program that computes the apparent contrast between the top of the high-rise building and the background sky, together with the corresponding values of visual range (in miles) using Koschmieder’s Law for a non-reflecting (black) target. At 0956 LST, the average contrast of the top of the high-rise against the background (printed as “horizon contrast” in Fig. 7) equals 0.076. When this observed value is compared with the threshold value of 0.055, it is evident that the visibility is greater than the 1 mile distance of the building. The automated telephotometer computes 1.5 miles for the visual range (“horizon visual range” in Fig. 7). At 1204 the instrument determines a visual range just over 2.7 miles corresponding to a contrast value of 0.24, which is approximately three times that observed at 0956. At 1322, the visibility conditions have improved to almost 4 miles. This visibility improvement with time can be observed in the image displays of Fig. 6. More accurate computations of visual range from the measured contrast values must include the reflectivity (non-black) characteristics of the high-rise building.

5. Further development

The telephotometer can operate unattended at remote locations. Using the prototype system, SRI has
initiated remote control of target scanning and data acquisition by telephone command to the acquisition computer. Tests have been made to transmit the acquired brightness measurements via telephone line to off-site storage and processing. The feasibility of this approach has been established.

The performance of the automated telephotometer has been evaluated primarily under conditions of relatively high visibility. Limited operation of the instrument during fog with visibilities around 1 mile demonstrates that the instrument has considerable potential for low-visibility monitoring at airports. Further feasibility tests, however, are required. [The use of television techniques to secure better information on visibility at airports near the flight path has been discussed by Douglas and Booker, 1977; a limited operational application is described by Etienne and De Swert (1983).]

The prototype system is available for such feasibility tests under low-visibility conditions, and current system documentation allows reproduction in small quantities for research uses. For any large-scale operational application, such as airport monitoring, an engineering design adapted to the particular environment and use will be required.

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