

APPLICATIONS OF A SENSITIVE TELEVISION SYSTEM

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Photoemissive image devices are very useful for low-light applications because of their inherent high quantum efficiency. This paper describes some of the characteristics of a sensitive television camera utilizing the recently developed Secondary Electron Conduction tube. The camera is being considered for a variety of low-light applications, including night-time meteorology and precise attitude measurement from earth satellites.

Sensitive photoemissive imaging devices have been receiving increasing attention in recent years for a wide range of challenging applications. Some of the more sensitive of these devices can detect visible radiation which is fainter by ten times than that which can be detected by the dark-adapted human eye. A photoemissive device with good resolution and signal-integrating capability, when coupled to an efficient lens system, can closely approach the theoretical limits of performance. Some of the more potent applications of such devices are from a satellite in such areas as meteorology, geology, agricultural surveys, astronomy, and attitude measurement and control. Additional applications are found in night-time military reconnaissance from aircraft, and underwater exploration.

This article will deal chiefly with some of the

characteristics and applications of one of the more recently developed photoelectric devices, the Secondary Electron Conduction (SEC) image tube. The SEC tube utilizes the highly efficient S-20 photosurface in combination with an excellent storage and integration capability to detect images of very low incident flux. The SEC tube, in addition, possesses two important advantages over similar devices, such as the image orthicon. First, it has been shown to be more capable of reproducing movement at very low light levels. Second, the SEC tube can give a more reliable measurement of the absolute intensity of point sources. The diameter of a point source on the output video is an accurate indication of its total energy over a dynamic range of more than six orders of magnitude. It is this property which makes it especially useful for star camera work,

where the intensity as well as the position of a point source is often required. An experimental camera using the SEC tube has been constructed at APL, and is being considered for such satellite applications as night-time meteorology and attitude measurement by star-mapping.

The Perfect Imaging System

In order to judge a real system, it is always useful to compare the system with some concept of an ideal one in which all information incident upon the detector is collected and used with 100% efficiency. In other words, all incident photons are counted, identified as having originated at a particular position, and placed in a storage device of infinite capacity. The ideal system is relatively simple to define, but it is usually more difficult to define quantitatively how close a real system comes to the ideal one. The three performance parameters that provide a good measure of the quality of a detection system are detectivity, resolution, and storage capacity. These parameters are certainly not all-inclusive, for they say nothing about such parameters as distortion, cost, or complexity. Some of these less basic considerations sometimes strongly influence the choice of a device for a particular application.

Detectivity is defined as the reciprocal of the noise equivalent input power. It gives a measure of the minimum incident flux that is necessary for a signal-to-noise ratio of one. One of the goals of the image device manufacturer is to minimize all extraneous sources of noise within the device, and thus to maximize detectivity. The theoretical limit, of course, is determined by the quantum nature of light; one must detect at least one photon. An imaging system that detects every photon is said to have a detective quantum efficiency of 100%. Figure 1 illustrates the quantum efficiencies of several types of detector that are useful in the visible and near-visible region of the spectrum.¹

The best common denominator to use in a discussion of image system resolution is the Modulation Transfer Function (MTF) which can be related straightforwardly to both the lens system and the image device. Conceptually, the simplest method of measuring the MTF is by focusing the detection system on a point source of light. The subsequent read-out of this point source of light in the form of an electrical signal will result in some spreading of the point source,

¹W.A. Baum, "The Detection and Measurement of Faint Astronomical Sources," *Astronomical Techniques*, The University of Chicago Press, Chicago, 1962, p. 18.

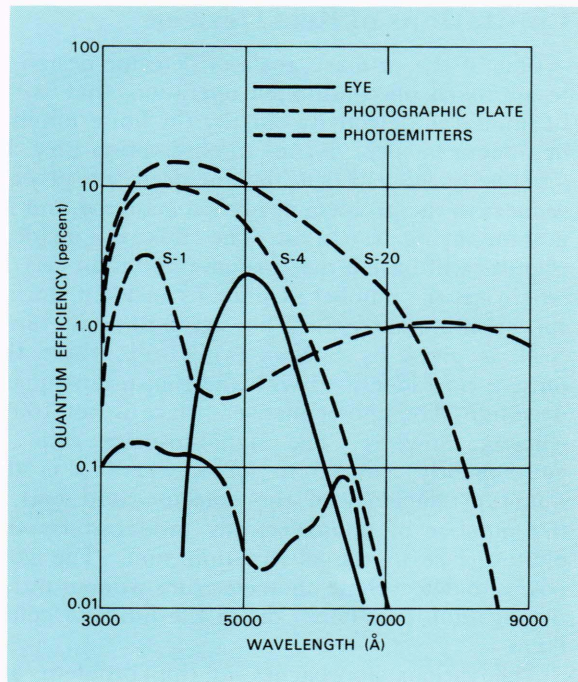


Fig. 1—Quantum efficiency of several detectors (after Baum).

owing, for instance, to aberrations in the lens system, or (in a photoelectric imaging device) to the finite width of the reading electron beam. The MTF is just the spatial Fourier transform of this point source intensity function. It is directly analogous to the impulse response of an electrical network in the frequency domain. A high resolution device has a high spatial bandwidth, where the spatial frequency is measured, for example, in cycles/mm, or line pairs/mm (lp/mm). The MTF's of several representative devices are shown in Fig. 2. Note the MTF of an ideal $f/15$ lens is limited only by diffraction. Whereas detectivity is limited by the quantum nature of light, the resolution of a perfect imaging system is limited ultimately by the wave nature of light.

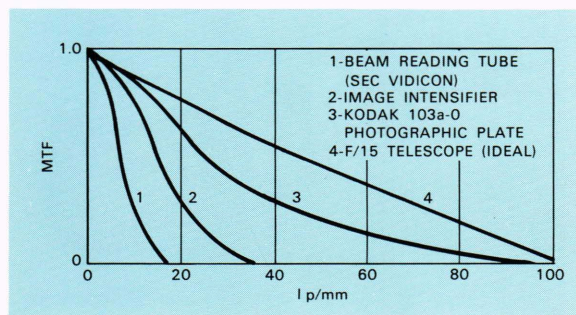


Fig. 2—Resolution of typical image devices.

Limitations of Real Devices

One of the primary goals of detector design is to approach photon-limited operation, that is, to be limited in detectivity only by the finite number of photons incident during an observation time. In a perfectly efficient detector, the detection process reduces to the problem of photon counting and its accompanying statistics. The flux of incident photons will have a mean-square deviation $\Delta n^2 = \bar{n}$ where n is the number of photons incident during the counting interval. The signal-to-noise ratio, S/N , is given by $S/N = \bar{n}/(\bar{n})^{1/2} = (\bar{n})^{1/2}$, where the noise is now identified with the root-mean-square deviation. The photoemissive surface is not 100% efficient, however. The signal-to-noise ratio is consequently reduced to $(q\bar{n})^{1/2}$, where q is the quantum efficiency of the detector, and $(q\bar{n})$ is the number of photoelectrons produced by the photosurface in the observation time. The goal now is to detect these photoelectrons without introducing additional noise, or, in the limit, to count them.

The various approaches to this problem are illustrated in the variety of image tubes existing today. In a typical image intensifier, the general design approach has been to accelerate the photoelectrons produced at the photoemitter through a high-voltage electric field (see Fig. 3). The high-energy electrons impinge upon a phosphor surface where they can re-emit several hundred photons per photoelectron. Noise in such a process originates from the release of spurious electrons from the tube interior surfaces. Accelerating the initial photoelectrons in a high voltage field is a method of amplifying the photoelectric energy without adding the noise that would be present, for instance, by sending the photocurrent through a resistor.

The resolution of most imaging systems with electronic output is limited by the spreading of the electron reading beam. Additional resolution

limiting can occur because of scattering processes in the photocathode surface, or in image intensifiers, in imperfect electron focusing. In some special cases where a very long focal length (narrow field of view) lens is coupled with a very high resolution tube, diffraction limiting and aberrations in the lens can become significant. Normally, however, the MTF of the lens-image tube combination is a direct measure of the spreading of the electron reading beam in the image tube.

The SEC Camera

The Secondary Electron Conduction tube represents a relatively new development in the category of sensitive imaging devices. The tube was originally developed by the Westinghouse laboratories with an ultraviolet photocathode for a star-mapping experiment in one of the Orbiting Astronomical Observatory satellites. Depending upon its application, it can be fitted with a variety of photocathodes. For applications in a normal low-light-level environment where most of the information tends to originate in the longer wavelength region, the extended red response of the S-20 photosurface is especially useful.

Figure 3 shows the basic construction of the Westinghouse WX30691 SEC tube used in an APL-built camera. Also shown is an optional image intensifier that can be mated to the basic SEC tube for increased sensitivity. Electrons from the photocathode of the SEC tube are accelerated through a 7kv potential, pass through a thin conductor, and strike a highly porous insulator. A positive potential on the signal plate, combined with an optimum velocity of 7kv electrons, causes ejection of secondary electrons from the insulator, leaving electron depletion in the insulator in the form of a charge pattern. The depletion will be greater in those areas where the image is bright, and will be less in the dark image areas. As the electron beam scans the surface of the porous insulator, beam electrons are attracted to the target in the area of charge depletion (bright areas) and are repelled in others. The beam electrons that are absorbed by the target pass through to the signal plate to form the signal current.

Secondary electron multiplication in the SEC target as described by Goetze² is between 100 and 200, and the minimum detectable signal is about 150 primary photoelectrons, or about 1000 photons at the peak sensitivity wavelength of the S-20 photosurface.

The SEC camera has appreciably less sensitivity

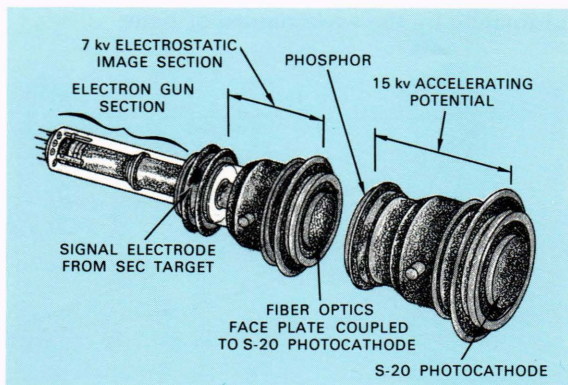


Fig. 3—The secondary electron conduction tube.

²G.W. Goetze, "Secondary Electron Conduction and its Application to Photoelectronic Image Devices," *Adv. in Electronics and Electron Phys.*, **22A**, 1966, 219-227.

than the unaided eye, which can detect about 30 photons at 5100Å. The maximum integration time of the eye, however, is only about 0.1 sec, while that of the SEC tube can be more than 100 sec. When mated to a 4-inch-diameter lens, for example, and allowed to integrate for 100 seconds, the SEC camera could detect stars close to magnitude 16, representing an improvement of 10^4 over that of the unaided dark-adapted eye, which can just detect 6th magnitude stars. In ground-based applications, atmospheric scattering in the foreground often prevents such performance. In a space vehicle, however, no such limit is present.

It is true, of course, that long integration times can only be used to advantage if the source and camera are relatively stationary with respect to each other. This is rarely the case in practical applications, and the maximum integration time is usually chosen by restricting image motion to about one resolution element on the tube face. For very short integration times, on the other hand, the detectivity of the SEC tube is limited by the electronic preamplifier noise. This limit can be overcome only by employing image intensification ahead of the SEC target as shown in Fig. 3.

Laboratory Experiments with the SEC Tube

Although substantial information is available on the SEC device in the literature, many of its characteristics (e.g., maximum permissible integration time) have not been reported in detail. The experimental camera has been developed with a wide range of parameter variability in order to gain additional information on its limitations and to permit evaluation for a variety of applications.

A diagram of the experimental arrangement used to collect data is shown in Fig. 4. A calibrated light source is contained at the left end of the 12-foot-long, completely-enclosed light pipe. An SEC tube with associated electronics is coupled to the opposite end of the light pipe. This light-tight arrangement facilitates a quantitative calibration of incident energy necessary in some of the tests performed. Electronic instrumentation necessary to operate the tube and the light source, as well as to analyze tube performance, is contained in two vertical racks shown at the extreme right in the figure.

Light is produced from a ribbon filament lamp operated at a color temperature of approximately 2870°K. The light is then filtered through a medium bandwidth (300Å) filter centered at 6330Å. The use of the filter considerably simplifies the absolute calibration of the lamp in photons/cm² sec at the plane of the SEC faceplate. The

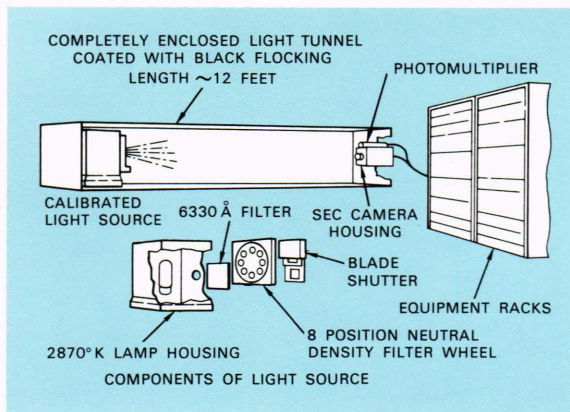


Fig. 4—Laboratory experimental arrangement.

intensity source is attenuated in steps of $10^{0.5}$ from 1 to $10^{3.5}$ by a rotary filter wheel containing a series of neutral density filters. The time duration of the source is determined with an electronically controlled two-blade shutter with variable exposure time from 3.1×10^{-2} to 1.0 sec. Longer exposure times are obtained by manually operating the shutter. The light source is calibrated in exposure time by measuring its duration with a photomultiplier and oscilloscope. Intensity calibration is obtained by calibrating the output current of the photomultiplier at one light level (through the 6330Å filter) with a calibrated solar-cell type power meter. The photomultiplier is thus calibrated in absolute units of amperes per incident energy flux.

Located within the camera head assembly are the preamplifier, beam control circuitry, and biasing electronics. Signal current of the order of 10^{-7} A maximum passes from the target through a load resistor located in the preamplifier. The preamplifier is composed of two integrated circuit amplifiers and has a transfer function of 1.5×10^6 V/A, a bandwidth of 10 Hz to 1.5 MHz, and an RMS noise current of 5.3×10^{-9} A. The maximum frequency response of the preamplifier must be high enough so that a transition from black to white may occur in a fraction of the scanning beam dwell time per resolution element. Unnecessary high-frequency response, however, decreases the signal-to-noise ratio of the video signal. Preamplifier input noise current is important, because it is directly related to the detectivity of the SEC tube, and is normally the prime contributor to system noise.

Figure 5 shows a simplified block diagram of the complete experimental arrangement. The SEC tube is turned on by sequentially applying biasing voltages by a series of automatically actuated time delay relays. The tube is scanned in a square

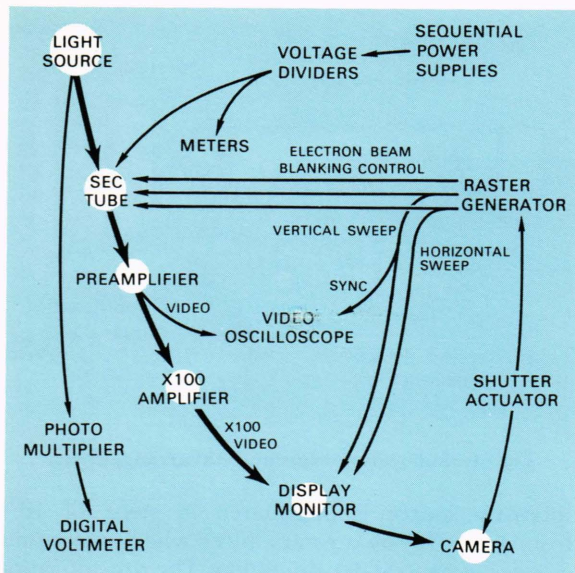


Fig. 5—Flow diagram of experimental arrangement.

raster with the number of lines variable up to 2048. The raster generator simultaneously scans both the SEC tube and a display monitor. Output from the tube is displayed by using the video signal to modulate the electron beam gun of the display monitor.

The normal mode of operation is as follows. The target of the SEC tube is brought to cathode potential by the sweeping electron beam, preparing the tube for exposure. The electron beam is then turned off and the deflection voltages are returned to voltages such that the electron beam will begin the proper raster scan. The camera is now exposed to light for a duration of up to 100 seconds. At the end of an exposure, the image information stored on the SEC target is read out with a single scan of the target and simultaneously displayed on a monitor. An oscilloscope camera whose exposure is synchronized to the single scan makes a permanent record of the image information. More than 90% of the information is read out in a single frame.

An alternate mode of operation is used when continuous motion must be observed. In this mode, the SEC tube is continuously exposed to light and is continuously scanned. Effective integration time is then identical to the frame time. Scan time is usually set in the order of 30ms. This mode is most useful in applications in which a continuous display of information is desirable, but is generally not as useful for sensitive astronomical applications, because of the necessarily short integration time.

With the aid of test patterns and the light-pipe assembly shown in Fig. 4, the performance of the

SEC tube has been measured under a variety of conditions. The limiting resolution (10% modulation) has been measured at about 12 line pairs/mm, or 480 lines across its 20-mm diameter. The tube can linearly integrate incident energy for times up to 100 seconds. This maximum permissible integration time corresponds roughly to the time that it takes background emissions from the photocathode to occupy an appreciable fraction of the information capacity of the SEC target. It is probable that cooling the camera would increase its maximum integration capability by minimizing background emission. Also, a more complex mode of operation in which, for example, the tube filament is turned off during exposure, might increase integration time. Such procedures have proven advantageous in the operation of the image orthicon.

Field Evaluation of the SEC Camera

The SEC tube has been mechanically coupled to a number of different lenses for field evaluation. It has been mated, for example, to a 76-mm focal-length f/0.8 lens resulting in a field-of-view of about 20 degrees, as well as to a 1250-mm f/15 catadioptric lens designed and built by R. Hires of APL. Some field testing has been conducted at night adjacent to the 60-ft. radio antenna at APL, but with only limited success. Scattered light from the local building complex limits exposure times to only five seconds with the catadioptric lens before the foreground illumination becomes overwhelming. Such an exposure allows detection of at least 6th magnitude stars, which is about equivalent to the limit of the unaided human eye on a clear night.

A slightly more satisfactory site has been found about one mile to the north of the main building complex. There the absence of the local lighting allows about twice the exposure time, and the 76-mm lens, operating with a two-inch aperture, limits between a 7th and 8th stellar magnitude.

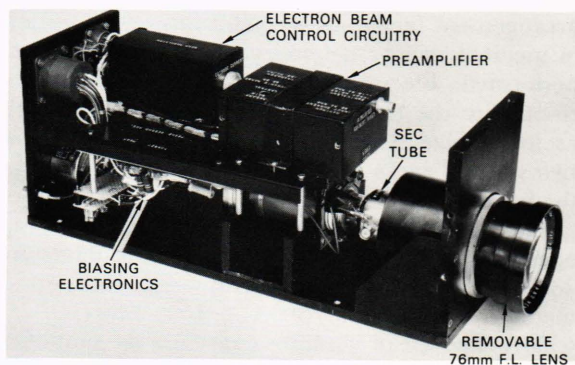


Fig. 6—Exposed view of SEC camera.

Figure 6 shows an exposed view of the camera head with the 76-mm lens. Figure 7 is a Polaroid photograph of a portion of the constellation Ursa Major taken by the SEC camera under the above conditions. Also shown is the corresponding section of the Bečvář Star Atlas. Stars of magnitude 7 are clearly visible.

Sky background unfortunately prevents exposures with the camera of more than about ten seconds in the Washington-Baltimore corridor. Figure 8 illustrates the potential performance of the camera

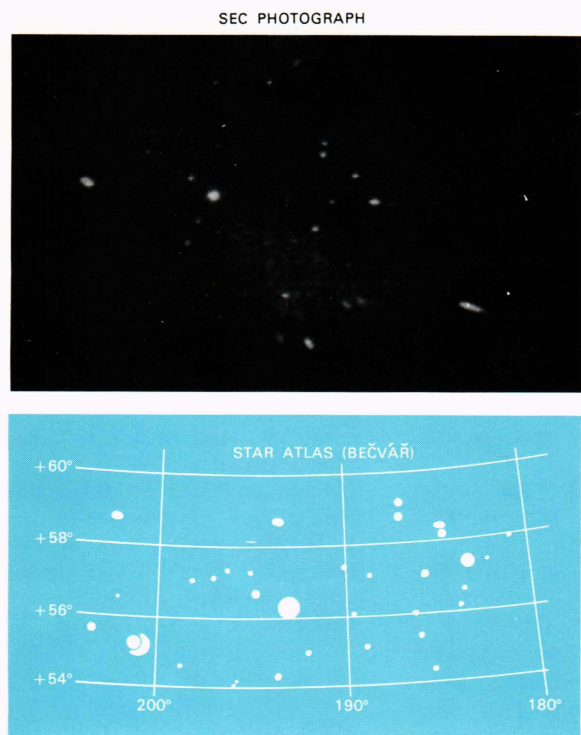


Fig. 7—The SEC camera in a star-mapping application.

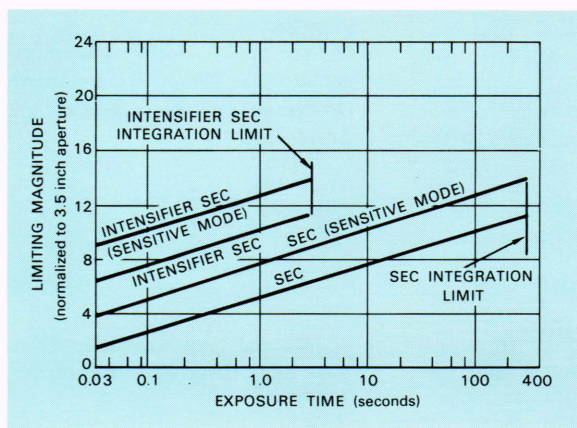


Fig. 8—Limiting sensitivity of the SEC camera.

in cases where exposure time is determined only by the properties of the camera tube itself. This would be the case, for example, in a satellite star-mapper application. The graph shows limiting sensitivity of the SEC camera as a function of integration time and lens diameter. Performance of both an SEC camera and an intensifier-SEC camera is shown in each of two modes. Two curves (nonsensitive modes) represent camera performance as it has been verified experimentally at APL and the improvement that could be expected by simply mating an image intensifier to the SEC tube. An improvement in sensitivity of an additional factor of 10 has been described in the literature³ in which the SEC target voltage is increased by about two volts between exposure and read-out. Combined with an increased target voltage, this method can yield an additional order of magnitude (or 2.5 stellar magnitudes) sensitivity improvement. This mode is shown in the remaining two curves.

The addition of an image intensifier cannot extend the ultimate detection threshold of the SEC camera. If exposure time is not a restriction, the threshold is reached when the background emission from the S-20 photocathode occupies a significant portion of the information capacity of the SEC target. The addition of an intensifier will increase the rate of information collection, but it will decrease the information saturation time by the same factor. The real advantage of an intensifier is in applications where short exposure time is a strict boundary condition, as, for instance, in a real-time continuous-scan mode of operation.

An SEC camera has received consideration for several satellite applications at the Applied Physics Laboratory. Used in conjunction with a photomultiplier, an SEC camera has been proposed for accurate attitude determination on the NASA Auroral Studies Satellite and on some of the Small Astronomy Satellites. Star mapping can be a very accurate way of determining the three body axes of a satellite. The accuracy is a function of the number of stars in the camera field-of-view which, in turn, is a function of the camera sensitivity. The SEC-photomultiplier measurement system is expected to permit attitude determination to ten seconds of arc.

Acknowledgment

The author is pleased to acknowledge the assistance of Mr. G.V. Bate for the mechanical design and construction of the camera head, as well as in many aspects of the experimental work and in the field testing of the camera system.

³R. R. Beyer, M. Green, and G. W. Goetze, "Point Source Imaging with the SEC Target," *Adv. in Electronics and Electron Phys.*, **22A**, 1966, 251-260.