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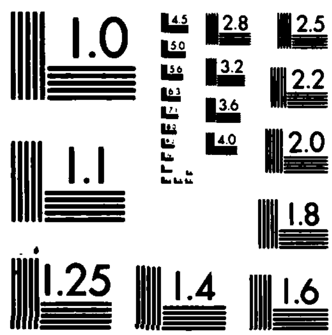
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AFGL-TR-83-0325

OPTICAL IONOSPHERIC MAPPING

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Final Report

July 28, 1980 - Sept. 30, 1983

15 December 1983

Approved for public release; distribution unlimited

AIR FORCE GEOPHYSICS LABORATORY
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE
HANSCOM AFB, MASSACHUSETTS 01731

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This report describes the support services provided by Keo Consultants to the operation and improvement of the All Sky Imaging Photometer on the NKC135 Airborne Ionospheric Observatory. It describes two new intensified camera systems constructed for the ground-based support of the airborne measurements and gives examples of the data obtained.

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1. Introduction:

In 1976-77 Keo Consultants designed and constructed an All-Sky Imaging Photometer (ASIP) for the Air Force Geophysics Laboratory (Contract F19628-76-C-0168). The system was installed on the NKC135 Airborne Ionospheric Observatory (AIO) in January, 1977 and has become a prime research instrument on the aircraft. The ASIP images a 165° field of view through four selectable 30 Å filters, and records images of ~20R intensity on both video tape and film. Research has been carried out in both the daytime and nighttime auroral regions, and in equatorial airglow regions. A full description of the instrument, and some applications, may be found in AFGL publication #TR-77-0155.

A second contract (F19628-77-C-0097, April, 1977 - Sept.,1980) was awarded as a follow on to F19628-76-C-0168, and involved the following:

(a) Improvements, modifications and repair of the ASIP as deemed necessary by consultation between AFGL and Keo Consultants.

(b) Keo participation in the planning of auroral and airglow experiments, and data analysis from these experiments.

(c) Design, construction and testing of a Digitization System to facilitate computer analysis of video tapes, and development of suitable software.

A full description of this work and instrumentation may be found in AFGL publication #TR-80-0326.

The present contract F19628-80-C-0153 (July, 1980 - Sept.,1983) continued Keo Support services for the ASIP and associated Digitization System, and also included the design and construction of two simpler ground-based film recording systems (all-sky and monochromatic) which have been fielded to support the airborne ASIP measurements. The requirement for these camera systems arose as a result of the HILAT program, which required the Ionospheric Effects Branch, Ionospheric Physics Division to provide support measurements over large spatial areas. Three of these instruments are presently installed in polar locations (one operated by Boston College in a cooperative program) and result in the coverage shown on the map in Figure 1.

Such large scale mapping of the aurora in polar regions allows derivation of auroral energy input, and the monitoring of the large scale movements of auroral structures that relate to F-region ionization patches. Such information is of direct interest to the HILAT radio-wave scintillation measurement program.

2. Maintennance and Improvements to the ASIP:

During the period of the contract, the ASIP was used on all research flights of the AIO, as well as for a series of ground based measurements. The instrument operated reliably and with few problems, and the minor problems that did develop were rectified quickly through the flexible arrangement between AFGL and Keo Consultants. The main difficulty that arose was an increasing unreliability of the IVC time lapse video recorders, and these were eventually replaced (August, 1982) with new Panasonic time lapse recorders.

As new investigations developed using the ASIP, Keo supplied a number of new narrow band interference filters to allow other emission features of interest to be studied.

AFGL also requested that two narrow field of view optics subsystems be designed, contructed and supplied to allow measurements at fields of view of 50° and 90°. These new front end optics were designed to simply mount in place of the present all-sky lens system, and were delivered to AFGL in August, 1983. An example of an image taken through the 90° field optics is shown in Figure 2. The picture shows a SF_6 chemical release from Wallops Island, Va. in Sept., 1983, as recorded with the ASIP from the AIO.

3. Mission Participation:

On request, Keo participated in mission planning and the supply of various equipment items for research flights throughout the contract period. Participation involved the following:

(a) Jan.-Feb.,1981: Ascension Island - Keo provided on loan to AFGL front end optics and an image intensifier to contribute to the ground based support for this mission.

(b) Jan.-Feb.,1982: Goose Bay-Greenland - Keo provided a keogram camera system on loan for use at Goose Bay, and a 16mm camera for flight use and participated in one flight out of Goose Bay with the CBS "Universe" television crew and Walter Cronkite.

(c) Sept.,1982: Brazil - Keo assisted in assembling a ground based all-sky intensified camera system for support of the mission.

(d) Dec.,1982-March,1983: Greenland - Keo assisted in making available a intensified all-sky camera system which AFGL installed at Sondre Stromfjord in support of research flights that supported the HILAT program.

4. Digitization System:

(a) Hardware: Problems were encountered with the special purpose Digitiz-atuon System provided under the previous contract. The problems primarily resulted from interface difficulties with the AFGL supplied Kennedy buffered digital tape recorder.

The equipment was returned to KEO in Dec.,1981 and various modific-ations and some improvements were made, but it was not possible to successfully integrate with the Kennedy recorder. First, the recorder had been modified by a previous contractor and no documentation was available. Second, it was an older Kennedy model and no longer supported by Kennedy service.

The data recording rate was slowed down to allow successful interfacing with a Kennedy incremental recorder, and the system with full documentation returned to AFGL in Nov.,1982.

(b) Software: Software was developed during the first year of this contract for analysis of the digitized ASIP data. This software included various plotting grids, gray scale and contour plots, and picture annotation. Considerable difficulty was encounted with the gray scale plotter at the AFGL computer facility, and in fact Keo personnel assisted in identifying and resolving some of the system problems. Software development was halted while the hardware problems were being resolved (see (a) above). As the contract progressed, a decision was made to upgrade the ASIP with a modern CCD detector system. At about the same time, a new gray scale/color plotter was announced for the AFGL computer facility. With this in mind, and given the rapid commercial development of relavent CCD image plotting software, it was deemed unprofitable to pursue further development of the software described above.

Consequently the Contract Monitor decided that the various software developed to date was not of immediate value to the program, and that no documentation of permanent programs was necessary to deliver under Line Item 0002AB of this contract. However it is expected that an effort to digitize all-sky film images from the new ground based cameras will be initiated in the near future. The mathematical basis of some of the software developed here would be relevant to such an effort. The appropriate parts of the software already developed will be made available for upgrading when this effort gets underway.

5. <u>All-Sky Monochromatic Intensified Cameras</u>:

In late 1980, a need arose for a simple ground-based instrument to monitor equatorial depletion regions from Ascension Island, see 3a. above, in association with simultaneous measurements from the AIO.

Keo conducted laboratory tests to demonstrate that a system that recorded on 35 mm film could achieve sensitivities of the order of 50 Rsec, more than adequate for the experimental requirements. A system was "pieced together" using Keo and AFGL supplied equipment and operated successfully at Ascension Island in Jan.-Feb.,1981.

Subsequently (April,1981) AFGL requested that Keo design and fabricate a complete ground based intensified camera system, with a four-position filter wheel and associated controls. Such a system was delivered to AFGL in Dec.,1981 and had the following features:

(a) All-sky field of view, telecentric optics.

(b) Four-position filter wheel with 25 Å filters, and including automatic and manual filter change and temperature control.

(c) Reimaging optics and Automax instrumentation camera, with LED data box.

(d) Shutter and controls for bright light protection, and automatic turn-on and turn-off.

(e) Varo 2nd Generation image intensifier

(f) Programmable controller for all instrument functions.

(g) Mounting rails and dome cover.

This instrument and associated controls is shown in Figure 3. It has now been used successfully in Brazil and Greenland.

In early 1983, AFGL recognized a requirement for a second identical instrument to support planned flights in the 1983-84 winter. Keo fabricated a second system and delivered to AFGL in August, 1983.

6. Instrument Upgrading, Future Instrumentation Planning:

In early 1981, the possibility arose that the two NKC135 research aircraft used by AFGL groups would have to be reduced to one aircraft, so that all equipment on board would have to be readily removeable and re-installable on the aircraft. This possibility, combined with the fact that much of the present instrumentation was using outdated technologies, led AFGL to request that Keo develop a set of recommendations for a future complement of current technology optical instrumentation for the AIO.

Keo undertokk this task between Feb.-Sept.,1981 and presented recommendations at meetings at AFGL on March 18 and May 8 and Sept.18, 1981. Prime considerations included miniaturization, control versatility, most effective use of modern technology, and use of modern data aquisition and display instrumentation.

As a result of these recommendations, AFGL solicited in Feb.,1982 proposals to cover the design, construction and testing of the following new optical equipment for the AIO:

(a) A six-channel tilting filter scanning photometer

(b) Two scanning spectrometers

(c) A new CCD monochromatic imager

(d) Appropriate microprocessor control and data handling and display capability.

(e) Basic software to cover operation of the above instruments.

In association with the study carried out by Keo, an extensive review of state-of-the-art detectors was completed. Keo also prepared a scientific report entitled "Low Light Level Imaging Design" which was published as AFGL Report #TR-82-0308 in Oct.,1982, a copy of which is attached to this Final Report as Appendix 1.

7. Figure Captions:

Fig.1: Polar map showing the spatial coverage of the intensified camera array (at the 220 km level).

Fig.2: Intensified camera photograph of a SF_6 chemical release, taken with the 90^{o} field optics from the AIO.

Fig.3: The intensified camera, with control electronics.

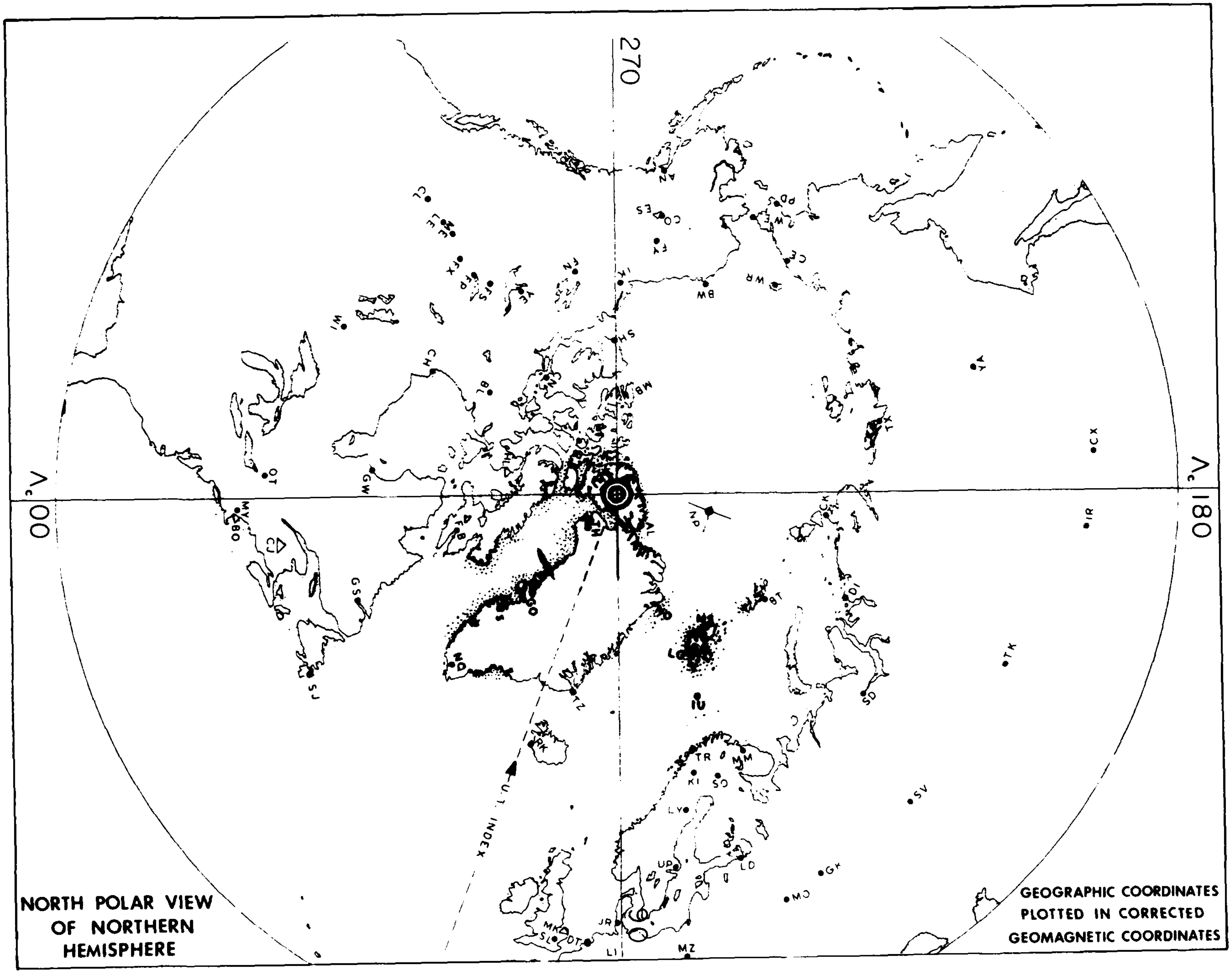
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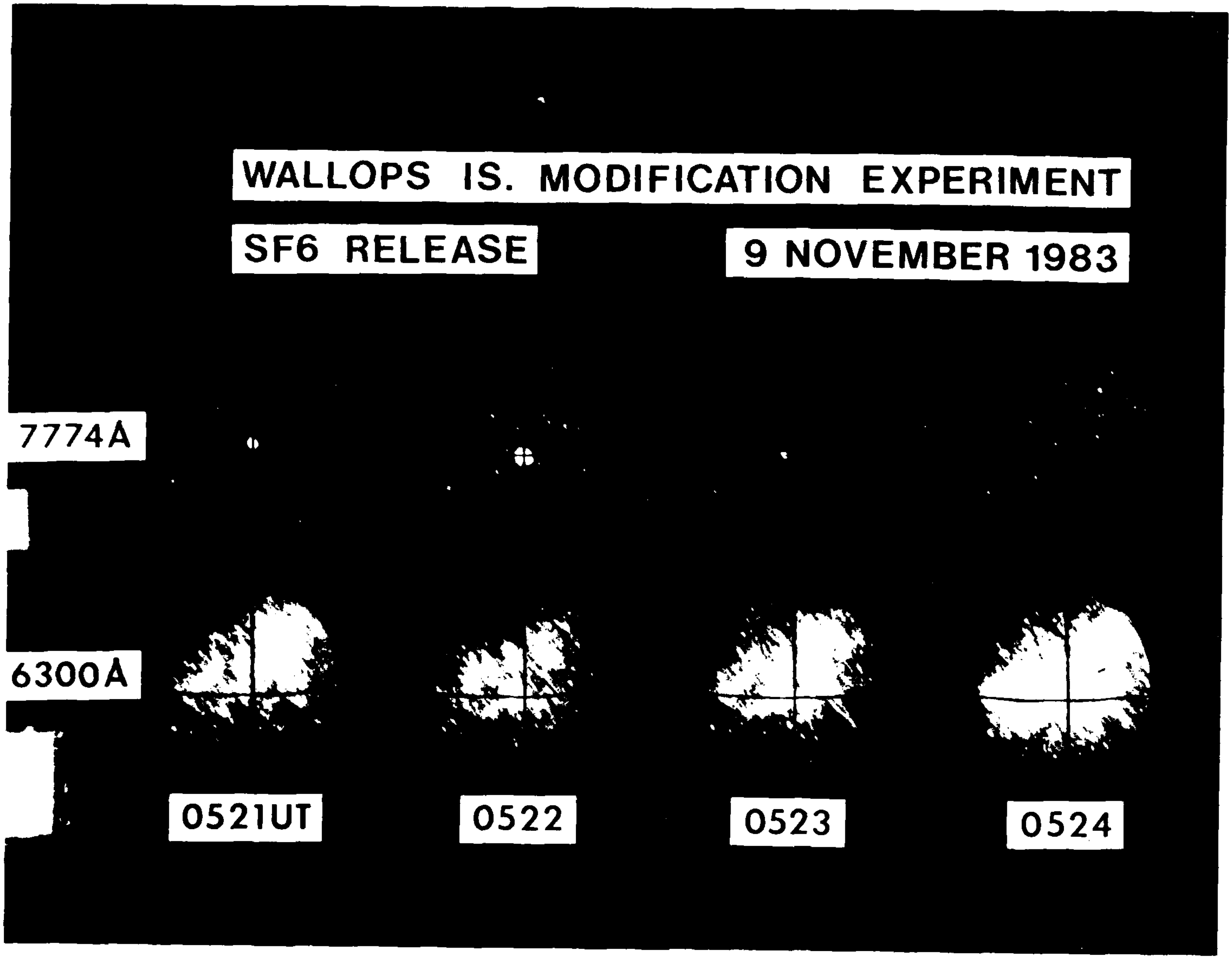
FIGURE 1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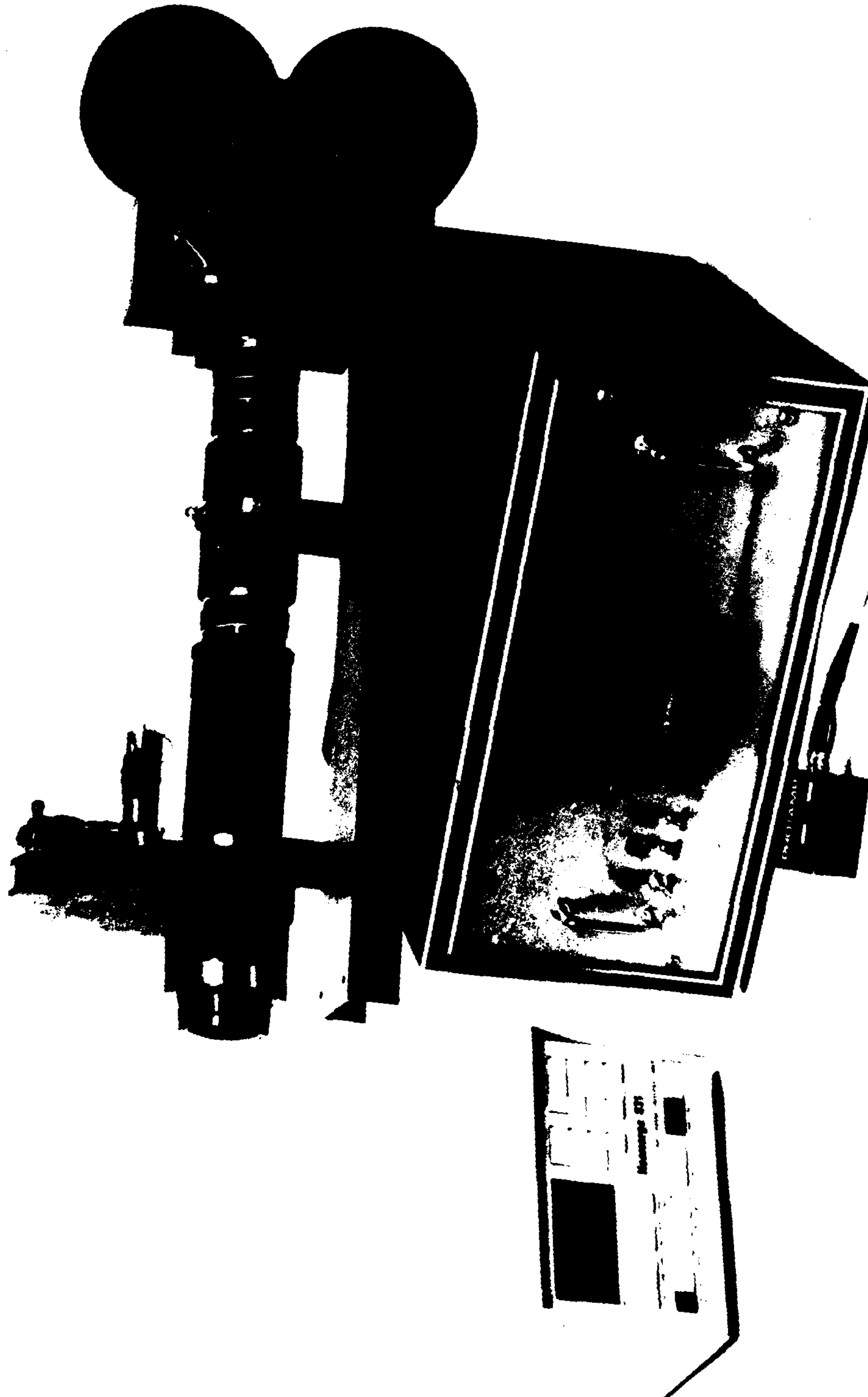


FIGURE 3

Appendix 1

Low Light Level Imaging Design

1. Introduction

Low-light-level imaging design involves evaluation of a number of variables that affect overall gain. Most systems include an image intensifier and some sort of recording device, such as film, a CCD array, or a TV camera. A list of factors that should be considered in design includes (though may not be limited to) input lens speed, filter transmission, spectral response of image intensifier, image intensifier gain, output phosphor spectral distribution, relay lens speed or fibre optics transmission, film speed (if used) or CCD or TV camera characteristics such as spectral response, sensitivity, and integration capability.

One normally has to rely on manufacturers' technical data for many of the above parameters, and these are often quoted in inconvenient or unfamiliar photometric units, often at an unspecified resolution. As a result, quoted "gains" or "sensitivities" of electro-optical devices may bear little relation to the specific problem being considered.

The purpose of this Report is to illustrate design calculations for a typical LLL imaging system that might be used in auroral or airglow research, and to provide appropriate explanations and definitions of the physical units one encounters in such calculations.

2. Definitions

2.1. Rayleigh: The unit of the *Rayleigh* is used widely in auroral and airglow research, and is somewhat equivalent to the radiometric term of *radiance*. Radiance is defined as the power leaving a surface per unit solid angle and unit projected area of that surface, and takes the units of watts per sq. cm per steradian, $Wm^{-2}\ sr^{-1}$. (This quantity is often called "surface brightness", an incorrect terminology because "brightness" is a perception sensation involving characteristics of the human eye.)

In auroral and airglow work, the important physical quantity is volume emission rate F in photons cm^{-3} sec^{-1}. If a "photon equivalent" of radiance, I, is obtained from measurements in units of photons cm^{-2} sec^{-1} sr^{-1}, then

$$4\pi\ I = \int_0^\infty F(r)\ dr$$

is the emission rate integrated along the line of sight, and has the units photon cm^{-2} $(column)^{-1}$ sec^{-1}.

The Rayleigh is defined as an *apparent emission rate* of 10^6 photons cm^{-2} $column^{-1}$ sec^{-1}. The "apparent" refers to the fact that no allowance has been made for scattering or absorption.

2.2. Lumen: Radiometric terms apply anywhere in the electromagnetic spectrum, and involve real physical quantities. Photometric terms, of which *lumen* is one, apply only in the visible part of the spectrum, and relate to the visual effectiveness of the light i.e. the sensation resulting in the human visual system. Conversion of radiometric to photometric units always involves the relative visibility of light at the wavelength being considered, the luminous efficiency (or photopic) curve (Figure 1). The ratio of any photometric unit to its radiometric equivalent is called luminous efficacy, e_λ (Table 1). The peak at 555 nm is the wavelength to which the "average eye" is most sensitive.

Table 1 STANDARD LUMINOSITY DATA

Wavelength	*Luminous efficacy*	*Wavelength*	*Luminous efficacy*
410	0.001	570	0.952
420	0.004	580	0.870
430	0.012	590	0.757
440	0.023	600	0.631
450	0.038	610	0.503
460	0.060	620	0.381
470	0.091	630	0.265
480	0.139	640	0.175
490	0.208	650	0.107
500	0.323	660	0.061
510	0.503	670	0.032
520	0.710	680	0.017
530	0.862	690	0.008
540	0.954	700	0.004
550	0.993	710	0.002
560	0.995	720	0.001

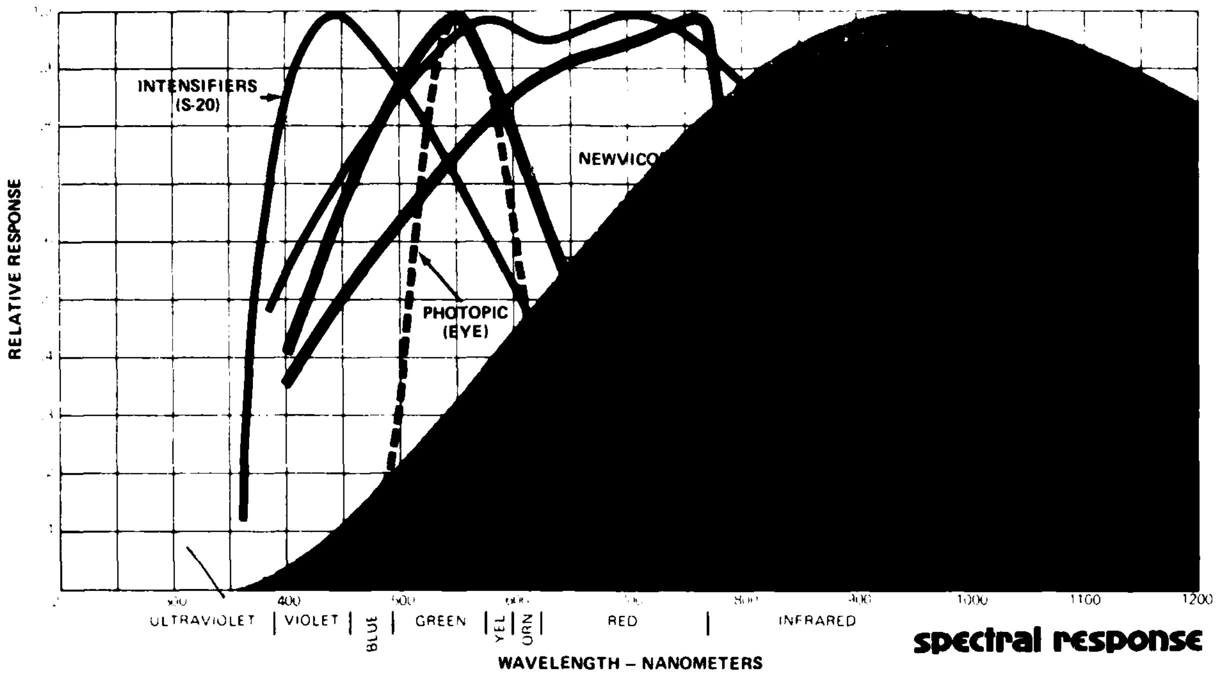
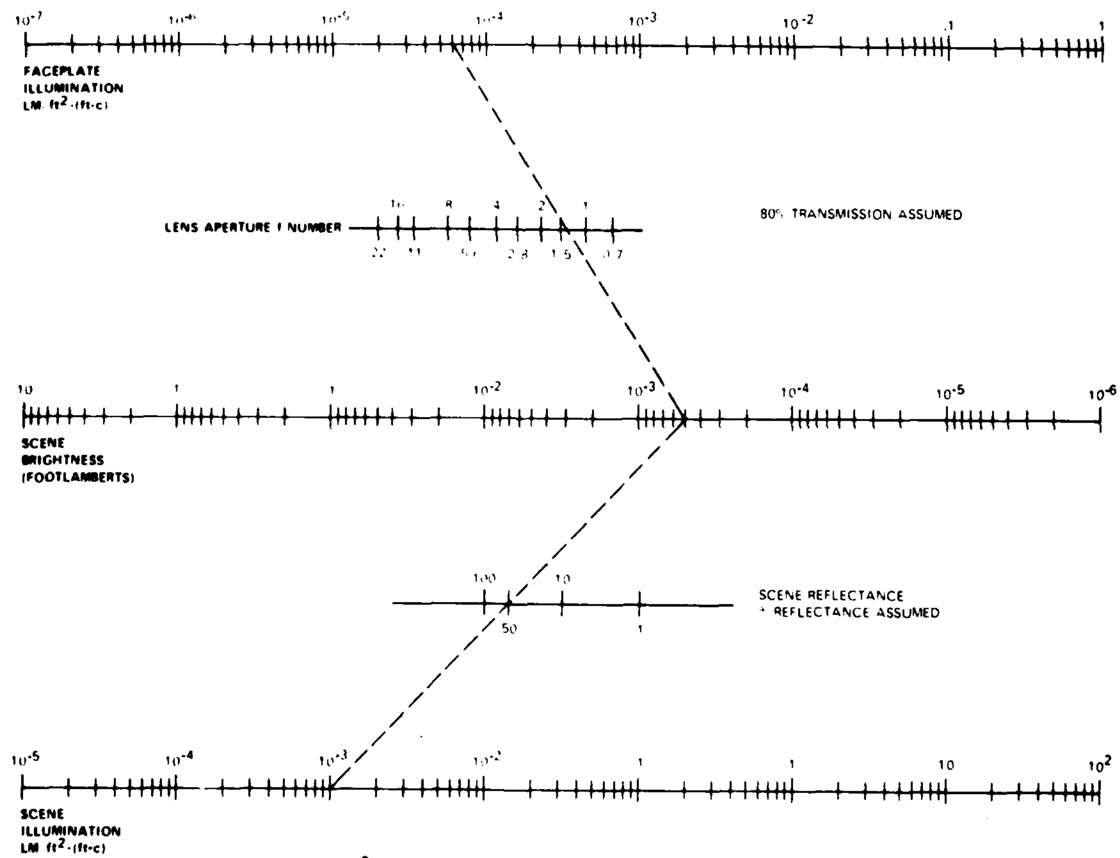


Fig. 1

APPLICATION NOMOGRAM



Example: It is an overcast night, and the scene illumination is considered to be approximately 10^{-3} lm/ft². Assuming a scene reflectance of 50%, a dotted line is drawn to the scene brightness line. This tells you that scene brightness is 5×10^{-4} fl. Using an f/1.4 lens on the television camera, the dotted line is projected to the faceplate illumination line. You now know that you have 6×10^{-5} faceplate illumination lm/ft². Referral to data sheets of television cameras will now isolate those that will permit you to televise from the area you have selected.

Figure 2

The radiometric unit of *power*, or energy transferred per unit time, is the *watt*: 1 W = 1 joule sec^{-1}. The photometric equivalent, *luminous power*, is the quantity of radiant power that produces a visual sensation to a human observer, and has the units of lumens.

At a wavelength of 555 nm, 1 lumen = $\frac{1}{680}$ W, or 1W = 680 lumen. At any other wavelength, this conversion must be multiplied by the luminous efficacy. For example, at 630 nm the luminous efficacy is 0.265 so 1 W = 680 x .265 = 180 lumen.

2.3. Illuminance: The radiometric term for radiant power incident on a surface is *irradiance* in W m^{-2}. The photometric equivalent is *illuminance*, E, which is the luminous power incident on a surface, in *lumen* m^{-2}, or *lux*.

The input power incident on an image intensifier or TV camera tube is usually specified by the manufactures in *foot candles*. This is an antiquated unit whose use should be discouraged, and is defined by

$$\begin{aligned} 1 \text{ ft. candle} &= 1 \text{ lumen ft}^{-2} \\ &= 10.76 \text{ lumen m}^{-2} \\ &= 10.76 \text{ lux} \end{aligned}$$

2.4. Luminance: The radiometric term for radiant power leaving a surface is radiance in W m^{-2} sr^{-1}. The photometric equivalent is *luminance*, L, which is the luminous power leaving the surface, in *lumen* m^{-2} sr^{-1}.

The output power leaving an image intensifier is usually specified by the manufactures in *foot-lamberts*. This is an antiquated unit whose use should be discouraged, and is defined by

$$\begin{aligned} 1 \text{ ft. lambert} &= \frac{1}{\pi} \text{ lumen ft}^{-2}\text{sr}^{-1} \\ &= 3.43 \text{ lumen m}^{-2} \text{ sr}^{-1} \end{aligned}$$

2.5. Nomogram: A useful nomogram relating illuminance, luminance, and LLL camera parameters, is given in Figure 2.

2.6. Conversion to Rayleighs: To find the Rayleigh equivalents of the above units, two conversions must be made, viz: from photometric units to radiometric (energy) units, and then from energy units to photon units.

The energy associated with a photon of a given wavelength is given by:

$$E_\lambda = \frac{hc}{\lambda}$$

$$= \frac{1.986 \times 10^{-9}}{\lambda} \text{ erg photon}^{-1}\text{, with } \lambda \text{ in nm.}$$

Therefore 1 ft. candle = 1 lumen ft^{-2}

$$= 1.07 \times 10^{-3} \text{ lumen cm}^{-2}$$

$$= \frac{1.07 \times 10^{-3}}{680 \times e_\lambda} \text{ W cm}^{-2}$$

$$= \frac{1.07 \times 10^{-3}}{680 x e_\lambda x E_\lambda} \times 10^7 \text{ photons cm}^{-2} \text{ sec}^{-1}$$

$$= 7.92 \times 10^9 \times \frac{\lambda}{e_\lambda} \text{ photons cm}^{-2} \text{ sec}^{-1} \quad *$$

1 ft. lambert $= \frac{1}{\pi}$ lumen ft^{-2} sr^{-1}

$$= 2.52 \times 10^9 \frac{\lambda}{e_\lambda} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1} \quad *$$

$$= \frac{4\pi \times 2.52 \times 10^9}{10^6} \times \frac{\lambda}{e_\lambda} \text{ Rayleighs}$$

$$= 3.17 \times 10^4 \frac{\lambda}{e_\lambda} \text{ Rayleighs}$$

For example, at 530 nm

1 ft. candle $= 4.87 \times 10^{12}$ photons cm^{-2}sec^{-1}

1 ft. lambert $= 1.55 \times 10^{12}$ photons cm^{-2} sec^{-1} sr^{-1}

$$= 1.95 \times 10^7 \text{ Rayleighs}$$

3. The Illuminating Light Source

When manufacturers quote an input sensitivity of an image intensifier or TV camera tube, they usually speak of a "usable picture" at a certain number of foot candles. There is often no specific definition of "usable picture", but one can probably assume it means a signal/noise ratio of ~2. An even more serious defect in manufacturer's specification sheets is that they often do not specify the light source used when obtaining sensitivities in foot candles. Unless specified otherwise, one can usually assume the light source used is a ~75W incandescent light bulb i.e. a tungsten source with a color temperature of 2854°K, closely equivalent to the Standard Illuminant A defined by the International Commission of Illumination (Figure 1).

Such a source has a spectral distribution that peaks in the near infrared, well outside the visible region. Hence if the photocathode has appreciable red and near infrared response, the gain figures that result may be quite unrealistic when one is considering the visible region. This is because when the illuminance is calculated from such a source, the irradiance is weighted by the luminous efficacy. Thus the peak energy outside the visible region does not contribute significantly to the illuminance, but does contribute to photocathode response. Table 2 lists data requied to estimate the tube response at a particular wavelength compared to that quoted by the manufacturer, for a typical S20/25 extended red photocathode (Figure 1).

It may be seen from column (5) in Table 2 that half of the tube response results from wavelengths above the visible region (> 700 nm), whereas none of this wavelength region contributes to the illuminance (column 4).

The *gain* of an image intensifier is defined by

$$\text{gain} = \text{luminance out}/\text{illuminance in}$$

Table 2

λ(nm)	(1) Relative watts 2854°K	(2) Luminous Efficacy	(3) Typical Sensitivity mA/watt	(4) (1)x(2)	(5) (1)x(3)
350	.016	0.	75.	.0	1.2
400	.050	0.001	88.	.0	4.4
450	.115	0.038	89.4	.004	10.2
500	.200	0.323	84.	.065	16.8
550	.325	0.993	75.	.313	23.6
600	.440	0.631	65.	.278	28.6
650	.630	0.107	55.	.067	34.6
700	.680	0.004	45.	.003	30.6
750	.780	0.	34.	.0	26.5
800	.860	0.	23.	.0	19.8
850	.920	0.	13.	.0	12.0
900	.970	0.	5.	.0	4.8
950	.990	0.	1.	.0	1.0

If one imagines a perfect transmitting diffuser, with no transmission losses and a Lambertian output, then 1 ft. candle incident illuminance will give 1 ft. lambert output luminance, and we can define this as a *gain* of 1. This is the concept of gain that is used when tube manufacturers quote their figures, except there are completely different input and output spectral shapes. Consequently the quoted gains are difficult to relate to any meaningful physical quantity such as photon gain at a specific wavelength.

For example, the information in Table 2 allows one to calculate that for equal illuminance onto the image intensifier (ft. candles), the gain at 550 nm would be 25% of that for a 2854°K source. On the other hand, for equal irradiance (W m^{-2}), the "gain" at 550 nm would be 238% of the gain for the 2854°K source.

To derive the associated *photon gain*, defined by

$$\text{photon gain} = \frac{\text{photons cm}^{-2}\text{ sec}^{-1}\text{ (incident on photocathode)}}{\text{photons cm}^{-2}\text{ sec}^{-1}\text{ sr}^{-1}\text{ (leaving output phosphor)}}$$

the spectral shape of the 2854°K light source (illuminant A), the photocathode spectral response, and the phosphor spectral output must all be considered. Suffice to say that in the 500-550 nm region, the photon gain is typically 25% of the quoted manufacturer's gain, and varies at other wavelength with the quantum efficiency of the cathode. This "photon gain" is similar to the "blue gain" quoted by some manufacturers, which is obtained by placing a pale blue filter (Corning #9788) in front of the 2854°K light source.

4. A Typical System

4.1 Faceplate Illuminance:

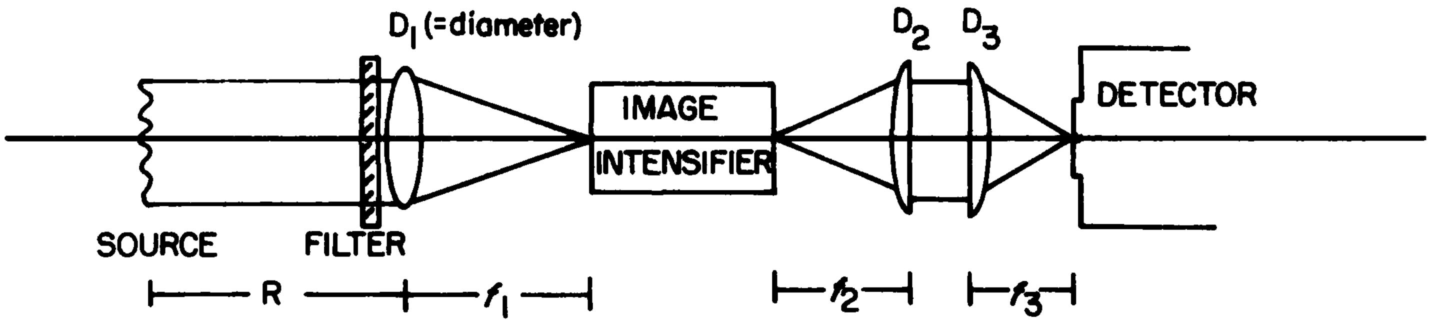


Figure 3

$$1\ R = 10^6 \text{ photons cm}^{-2} \text{ column}^{-1} \text{ sec}^{-1}$$

$$= \frac{10^6}{4\pi} \text{ photons cm}^{-2} \text{ sec}^{-1} \text{ sr}^{-1}$$

$$\text{No. steradians subtended by lens} = \frac{\pi D_1^2}{4R^2}$$

$$\text{Image magnification (area)} = \frac{f_1^2}{R^2}$$

Therefore, No. photons incident on 1 cm^2 of faceplate of image intensifier

$$= \frac{10^6}{4\pi} \cdot \frac{\pi D_1^2}{4R^2} \cdot \frac{R^2}{f_1^2} \sec^{-1}$$

$$= \frac{10^6}{16F_1^{\,2}} \sec^{-1} \text{ where } F_1 = \text{F no. of lens \#1.}$$

4.2 Relay Lenses:

Solid angle subtended by lens $= \dfrac{\pi D_2^2}{4f_2^2}$

Area magnification $= f_2^2/f_3^2 \; (D_3 > D_2)$

If L is the output luminance of the image tube, then number of photons collected

$$= L \times \frac{\pi D_2^2}{4f_2^2} \cdot \frac{f_2^2}{f_3^2} = \frac{\pi DL_2^{\,2}}{4f_3^{\,2}}$$

$$\text{Loss factor} = \frac{\text{No. photons collected}}{\text{Total emitted (assumed Lambertian)}}$$

$$= \frac{D_2^2}{4f_3^2}$$

If both lenses are F1.2, then

Loss factor = .174

Note that an alternate means of coupling would be directly by fibre optics. The acceptance cone angle for a typical fibre optics coupler is ~41°. This corresponds to a numerical aperture of 0.66, and compared to the total light emitted (assumed Lambertian),

Loss factor = (numerical aperture)^2

= 0.44

Thus fibre optics is some 2.5 times more efficient as a coupler than a pair of F1.2 relay lenses.

4.3.1. Assume:

input lens	F 1.2
relay lenses	F 1.2
filter transmission T	0.75
transmission t (relay lenses)	0.75
intensifier gain	5×10^4 ("manufacturer's gain" for 2nd Gen. intensifier)
output phosphor	P20 (530 nm peak)
input λ	530 nm

Then for 1 R of source

No. photons reaching faceplate of image intensifier (see section 3) $= \dfrac{10^6}{16 \times 1.2^2} \times T$

$= 3.25 \times 10^4$ photons cm^{-2} sec^{-1}

[$= 6.67 \times 10^{-9}$ ft. candles (at 530 nm)]

Effective gain (photon gain) $= 5 \times 10^4 \times \dfrac{1}{4}$

$= 1.25 \times 10^4$

Therefore Output* $= 3.25 \times 10^4 \times 1.25 \times 10^4$

$= 4.06 \times 10^8$ photons cm^{-2} sec^{-1} sr^{-1}

[$= 2.62 \times 10^{-4}$ ft. lambert (referred to 530nm)]

After relay lenses, illuminance* at the detector plane is given by

$4.06 \times 10^8 \times .174 \times t$

$= 5.31 \times 10^7$ photons cm^{-2} sec^{-1}

[$= 1.09 \times 10^{-5}$ ft. candles (referred to 530 nm)]

*Note: These photons will actually have a spectral distribution determined by the output phosphor.

Thus the effective photon gain of the complete system i.e. the ratio of no. of photons reaching detector faceplate to no. incident on image intensifier faceplate

$$= \frac{5.31 \times 10^7}{3.25 \times 10^4}$$

$$= 1.63 \times 10^3$$

4.3.2. Noise considerations

a) Thermal. A typical noise equivalent input for a 2nd Gen image intensifier is $\approx 10^{-11}$ lumen cm^{-2} (referred to a 2854°K source),

$$\simeq 10^{-8} \text{ ft. candles.}$$

From above, 1R at 530 nm corresponds to 6.67×10^{-9} ft. candles reaching the faceplate. Therefore, thermal noise is approximately equivalent to

$$\frac{10^{-8}}{6.67\text{x}10^{-9}} \times \frac{\text{manufacturer's gain}}{\text{photon gain}}$$

$$\sim 6 \text{ R}$$

(this noise could be essentially eliminated by moderate tube cooling).

b) Statistical. To obtain a useable picture, the final detector must receive enough photons so that the signal/noise ratio exceeds ~ 2:1 for each resolution element. At the very low light levels that we are considering, we are essentially photon limited, so the statistical noise situation is determined by the number of photoelectrons generated at the image intensifier cathode and the number of resolution elements.

Assuming 1R of input, 256 x 256 resolution elements, and 15% quantum efficiency, then the number of photoelectrons generated per resolution element of the image intensifier cathode

$$= \frac{3.25 \times 10^4 \times 0.15}{256 \times 256}$$

$$= .074 \text{ per resolution element per sec.}$$

Thus to achieve 4 photoelectrons per resolution element per sec, (S/N = 2:1) we need an input of ~ 54R sec (eg 54R integrated for 1 sec). It is clear then that we are in a photon limiting situation, and the noisiness of the final picture is <u>independent of system gain</u> (provided the gain is sufficient so that each photoelectron results in a measurable light output pulse at the final detector). This calculation illustrates that it is essential to have time integration at the final detector in order to obtain a usable picture at these high levels.

Given that fact, final sensitivity is determined by acceptable time resolution and the maximum time the final detector can effectively integrate.

4.3.3 Final Detection:

Consider three cases for the final detector: film, a TV camera, and a CCD array. Consider a source of 20R, which is a desirable limiting sensitivity in many auroral/airglow applications.

a). Film. Film is often used as a final detector because it is simple to use, has high resolution and can integrate exposures for long periods. (In this case the resolution is unimportant because limiting resolution is determined by the image ntensifier). The "quantum yield" for fast films is $\leq$ 1% i.e. only 1 in 100 quanta results in a photographic effect, but this effect is cumulative so long integrations are possible.

For a 20R source, the illuminance reaching the film is (see 4.3.1 above)

$$= 20 \times 5.31 \times 10^{7} \text{ photons cm}^{-2} \text{ sec}^{-1}$$

$$= 3.97 \times 10^{-3} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ (at 530 nm)}$$

For a usable film density, KODAK curves for Tri-X (400 ASA) show that

required illuminance is $> 5 \times 10^{-3}$ lux sec

$$= 5 \times 10^{-7} \text{ lumen cm}^{-2} \text{ sec}$$

$$= \frac{5 \times 10^{-7}}{680 \times .862} \text{ W cm}^{-2} \text{ sec at 530 nm}$$

$$= 8.5 \times 10^{-3} \text{ erg cm}^{-2}$$

Therefore, Required exposure $= \dfrac{8.5 \times 10^{-3}}{3.97 \times 10^{-3}}$

$$\sim 2.1 \text{ sec}$$

which conveniently matches the required integration times for acceptable picture quality (see 4.3.2.b above). Thus fast film (> 400 ASA) is ideally suited as a final detector for this situation.

b). TV Camera. If we assume 256 x 256 resolution elements for the TV faceplate (the same as assumed for the image intensifier, see 4.3.2.b. above), then for a 20R source, the numbers of activations of each resolution element per TV field (1/60 sec) is given by

$$0.74 \times 20 \times 1/60$$

$$= .025$$

i.e. only 1 in 40 resolution elements of the TV faceplate will be activated in each TV field.

However, each activation will be created by a light pulse of 1.63×10^3 photons (see 4.3.2.b above), or as high as $\sim 6 \times 10^3$ photons if fibre optics coupling is used instead of relay lenses. This range is about the input photon equivalent of amplifier noise in most TV camera electronics. Thus to detect these pulses in real time requires either

(i) additional external amplification eg. by adding a low-gain intensifier to the system

(ii) use of a TV camera with an integrated intensifier stage.

The required sensitivity of the TV camera detector is found by calculating the faceplate illuminance if all resolution elements received this number of photons (1.63×10^3) in 1/60 sec. If we assume a 16mm diag. faceplate (1.25 cm^2 picture area) then this illuminance is $\frac{1.63\ 10^3 \times 256 \times 256 \times 60}{1.25}$ photons cm^{-2} sec^{-1}

$$= 5.2 \times 10^9 \text{ photons cm}^{-2} \text{ sec}^{-1}$$

$$= 1.05 \times 10^{-3} \text{ ft. candles (referred to 530 nm)}$$

$$\sim 2.5 \times 10^{-4} \text{ ft. candles (referred to 2854°K)}$$

But because only 1 in 40 resolution elements are activated each field, the picture would be unusable. The TV camera must integrate for 2.7 sec. to give 4 activations per resolution element (S/N of 2:1).

Thus we require a LLL TV camera with a quoted manufacturer's sensitivity of $\sim 2.5 \times 10^{-4}$ ft. candles, and a capability of integrating effectively for $\sim$ 2.7 sec. The first requirement is readily met by many LLL TV cameras, but the intergration requirement is only possible with special tube types, such as the SEC type of camera, and moderate detector cooling may be desirable.

c). CCD array. In general, similar comments apply as those discussed for the TV camera. Typical arrays have more than adequate sensitivity, but the integration requirement still holds. Because of the noise levels of CCD arrays, cooling is necessary to achieve 2-3 sec integration times. Required cooling is moderate, ~-30°C. The cooled CCD array however, has significant advantages over film and the TV camera, in that exhibits less distortion, it can handle a much larger dynamic range, and its output is much more linear with light input.

5. Maximizing Sensitivity.

It is clear from the above discussion that the limiting factor in LLL performance is not detector gain, but photon noise limitations at the input photocathode. Once a photoelectron is generated at the input, current image intensifier and TV tube technology ensures that a light pulse will be detected and displayed at the output.

The only way to improve input photon limitations are to

a) increacse efficiency of collecting optics.

b) Increase photocathode quantum efficiency. This might be achieved by selecting photocathodes for particular spectral regions, but in general the S-20 and its variants are the most suited for auroral/airglow research. Galium arsenide photocathodes may be more suited for surveillance applications.

c) Use a minifying image intensifier (with the same output screen resolution). For example, a 40mm → 25mm image tube results in an increase in cathode collecting are of ~ 2.5 for each resolution element of the output screen. Such intensifiers are available in 1st Generation types, but significant minification is not yet available in

2nd Gen tubes. (Note too that suitable input optics must be available to use the larger input area at a similar F number to the non-minified system).

6. Manufacturer's "Sensitivity".

To obtain a usable picture (S/N = 2:1) in real time, the above discussion shows that the source integrated emission rate would have to be 3.2 kR. This might be reduced to ~2kR with faster input optics, which corresponds to $\sim 10^{-5}$ ft. candles faceplate illumination (see 4.3.1). These numbers are referred to a 530nm source, and would be reduced to $\sim 2.5 \times 10^{-6}$ ft. candles for the 2854°K source usually used by tube manufacturers.

This faceplate illuminance represents the limit for obtaining a useable picture (S/N = 2:1) at a resolution of 256 x 256. One should view quoted manufacturer's sensitivities which are less than this number with some scepticism, as lower numbers imply one or more of the following

(i) S/N ratio less than 2:1

(ii) resolution less than 256 x 256

(iii) extended red cathode sensitivity (which increases the response to a 2854°K light source, but does not affect the number of lumens contributing to faceplate illuminance).

(iv) a test light source "redder" than a 2854°K source

(v) effective integration by the eye (at low light levels, the human eye effectively integrates for ~0.1 sec, and so a picture might be judged "usable" in some situations by a human observer, whereas individual TV frames would not be judged usable.

(vi) effective integration by tube lag effects for some types of TV tubes.

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