August 31, 1987

INVESTIGATION INTO THE DEVELOPMENT OF

COMPUTER AIDED DESIGN SOFTWARE

FOR SPACE BASED SENSORS

FINAL REPORT

Contract No: NAS5-30061

SBIR 86.1   08.22-7211

BY

C. W. Pender, Ph. D.

W. L. Clark

Submitted by:

Tennessee Space Laboratories, Inc.
P. O. Box 728
Manchester, TN 37355

Submitted to:

NASA/Goddard Space Flight Center
Engineering Procurement Office, Code 287
Greenbelt Rd.
Greenbelt MD   20771

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE   PAGE

Project Summary

The described effort is phase one of the development of a Computer Aided Design (CAD) software to be used to perform radiometric sensor design. The software package will be referred to as SCAD and is directed toward the preliminary phase of the design of space based sensor systems. The approach being followed is to develop a modern, graphic intensive, user friendly software package using existing software as building blocks. The emphasis will be directed toward the development of a shell containing menus, smart defaults, and interfaces, which can accommodate a wide variety of existing application software packages. The shell will offer expected utilities such as graphics, tailored menus, and a variety of drivers for I/O devices. Following the development of the shell, the development of SCAD is planned as chiefly selection and integration of appropriate building blocks.

The phase one development activities have included: the selection of hardware which will be used with SCAD; the determination of the scope of SCAD; the preliminary evaluation of a number of software packages for applicability to SCAD; determining a method for achieving required capabilities where voids exist; and then establishing a strategy for binding the software modules into an easy to use "tool kit".

During phase two the SCAD software will be implemented. Phase two activities will consist of: continuing the evaluation efforts of pertinent software; selecting the software packages which will be used; developing the shell which will be used to tie the modules together; and providing the required graphics, device drivers, menus, and the like.

Phase three activities will consist of: marketing the SCAD software, extending the SCAD capabilities, and using the same techniques to address other problems which can be solved with established, but unwieldy software.

1.0   INTRODUCTION

The described effort is phase one of the development of a Computer Aided Design (CAD) software to be used to perform radiometric sensor design. The software package will be referred to as SCAD and will be directed toward preliminary design of space based sensor systems (Fig.1). The approach being followed is to develop a modern, graphic intensive, user friendly software package using existing software as building blocks. The emphasis will be directed toward the development of a shell, containing menus, smart defaults, and interfaces, which can accomodate a wide variety of existing application software packages. The shell will offer expected utilities such as graphics, tailored menus, and a variety of drivers for I/O devices. The goal of the shell development will be twofold. First the shell will produce a SCAD software package meeting the immediate requirements. Second, the shell software methodology will be established to implement other software tools using many other existing, hard to use software packages. The development of the shell is anticipated to be the most substantial effort in producing SCAD; in fact, the SCAD is viewed as an example of how the shell may be used.

Following the development of the shell, the development is planned as chiefly selection and integration of the building blocks. This first phase of the development consisted primarily of determining the scope of the software required to implement SCAD (see Fig. 2 for overivew of SCAD scope) and the hardware required to implement it. The secondary objective of this investigation phase of the development was to begin, where possible, evaluating available software packages for applicability to the problem at hand, determining a method for achieving required capabilities where voids exist, and then establishing a strategy for binding the software modules into an easy to use "tool kit".

The software will be developed to answer the need specified in the SBIR request 86-1.

"NASA would like to develop the capability to model instruments, proposed for observations of the Earth's land surface, using CAD techniques, a task which is expected to involve a great deal of creativity and innovation. These models need to specifically possess functionality to simulate the effect of varying aperture size, focal length, detector material sensitivity and efficiency, electronics amplifications, etc., in order to conduct sensitivity analyses and trade studies. Methods must be developed for interfacing the CAD software for instrument design to existing NASA models of radiation reflectance distribution expected from land surface features, as modulated by atmospheric effects on the radiation. Methods must also be developed for graphically displaying the results of simulation runs utilizing CAD software."
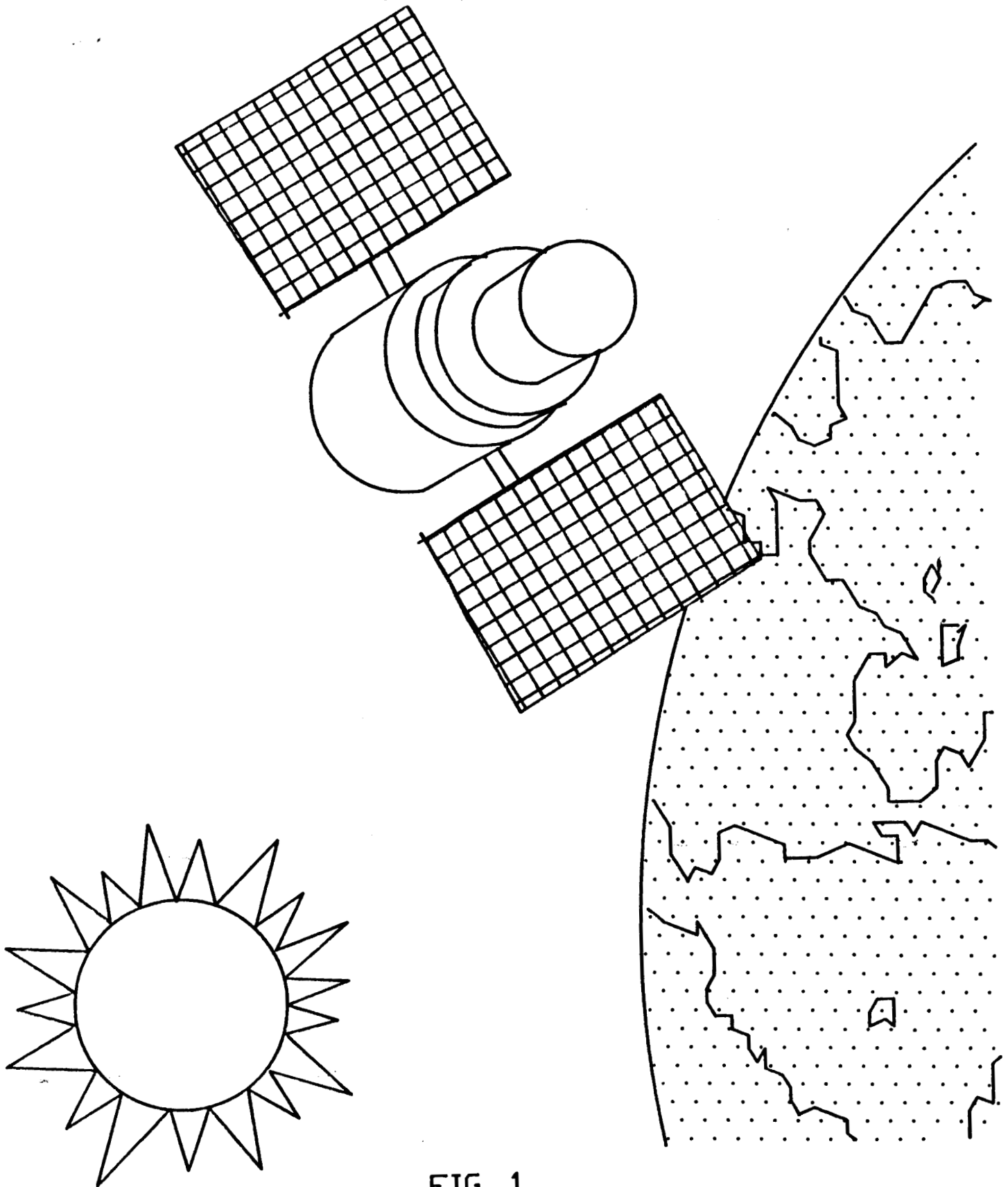
FIG. 1
PAGE 3
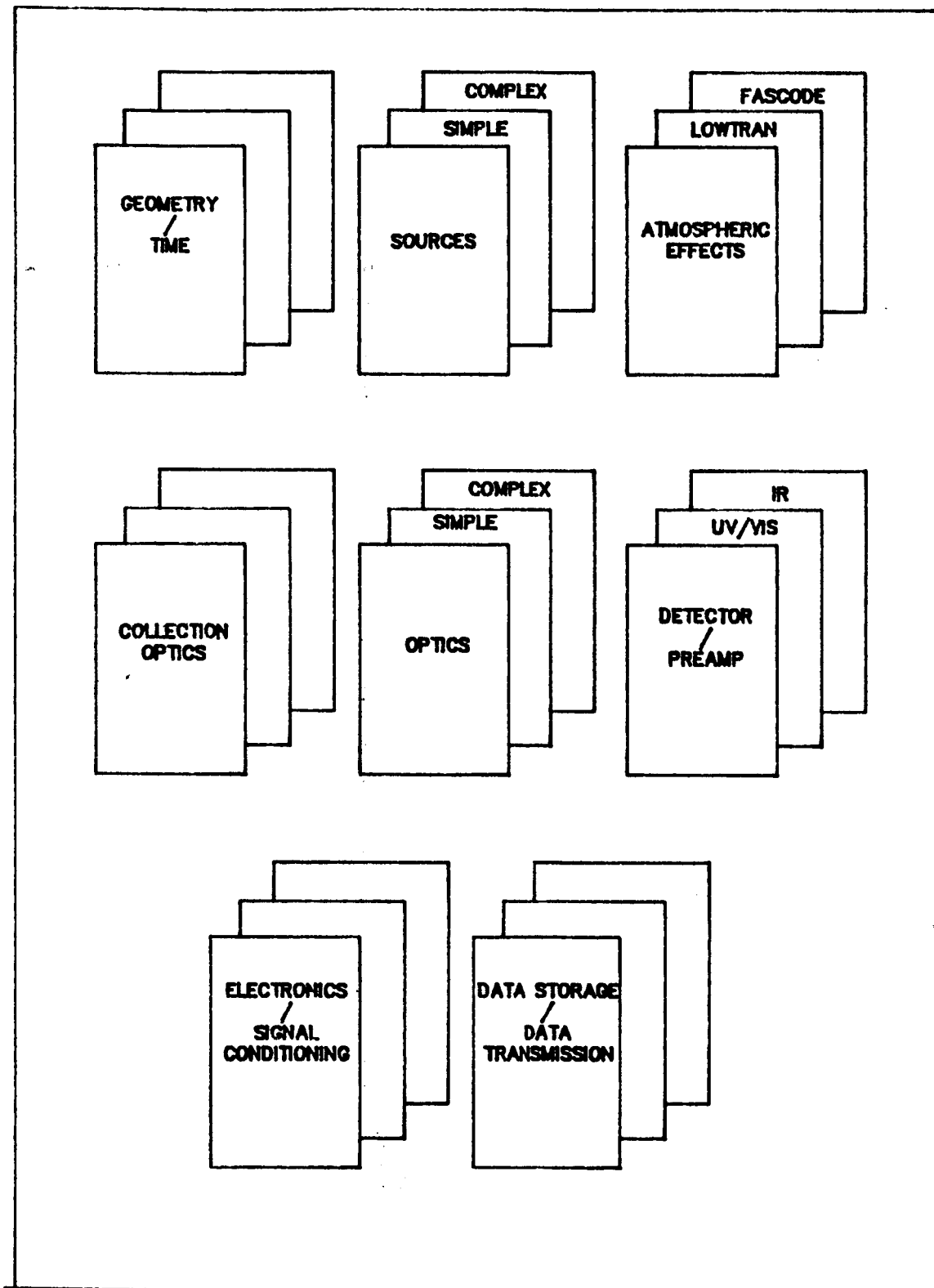
SCAD OVERVIEW

Fig.2
Page 4

A primary objective, following performance, is to build a usable ensemble of modules which can perform the total design. Good examples of what SCAD is not meant to be can be found in many widely advertised and used softwares which require weeks of training for modest returns in benefit. The best examples can be found in optical design, CAD, and elaborate project management packages. Most of these kinds of software packages require substantial training to be used. SCAD is intended to be quickly usable with minimal training. It will lead a user through the design, offering rational defaults and graphically illustrated choices, so that a first time user can profitably use it. SCAD is to be developed using many applications packages as building blocks; however, the user interface provided by SCAD should make the interaction with each block simple and understandable. Individual building blocks and their manuals will be included with SCAD so the dedicated user may delve more deeply into individual blocks if he so desires, but individual familiarity will not be required.

This description of the first phase of the development is broken into five parts. In section 2 the hardware selected for the initial implementation of SCAD is described. The next section provides the background, including nomenclature, describing the sensor scenario. This section addresses the major issues facing a sensor designer. The following section defines the scope of SCAD and some of the application software packages which are currently available that may be used to meet portions of the SCAD requirements. In section 5 the approach to merging the component softwares into a working SCAD is discussed. Section 6 deals with the graphics capabilities planned for SCAD. Section 7 deals with the graphics capabilities planned for SCAD. Section 7 deals with the potential of expanding the SCAD to encompass both more detailed design of space sensors and attacking other similar problems.

2.0   HARDWARE

The SCAD is being tailored to the personal computer domain since it was felt that it would find greatest utility there. Also knowing that PC's are rapidly becoming more

CGA or EGA

MONITOR

DIGITIZER

PLOTTER (optional)

IBM PC or AT

COPROCESSOR

640 K bytes RAM

FLOPPY DRIVES

20 M byte DISK

GRAPHICS PRINTER
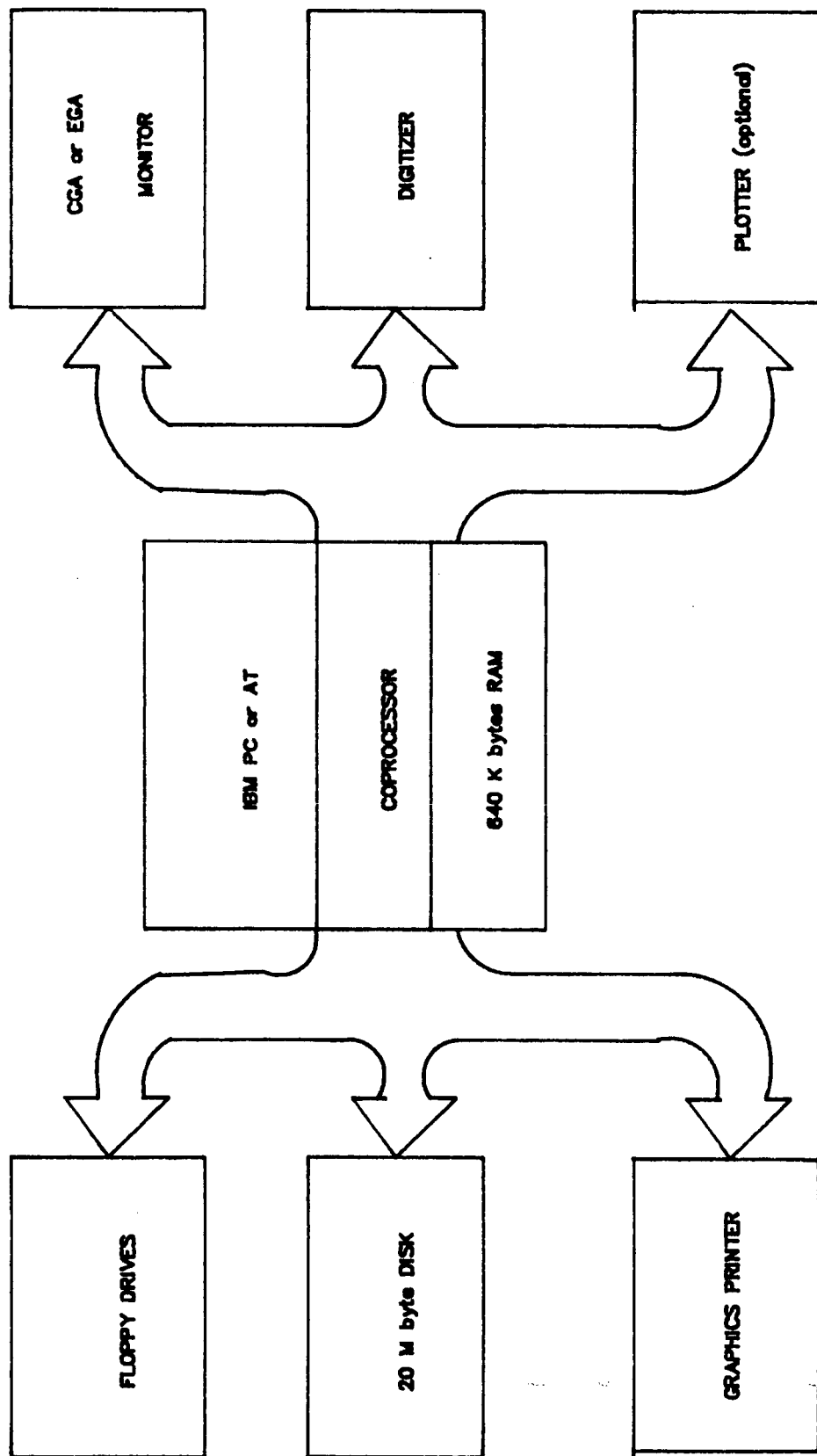
HARDWARE REQUIRED FOR SCSD

FIG. 3
PAGE 8

powerful with each upwardly compatible component being developed, SCAD can grow and run more rapidly in the future. The decision was mainly whether to use the Apple MacIntosh or the IBM PC as the host machine. Due to the expandability, the industry acceptance, and the large number of IBM PCs (or clones) in use, the PC was selected. The minimal machine is a IBM PC with 640 kbytes of RAM, a 20 Mbyte hard disk, a mouse, a floppy disc and a moderate to high resolution monitor. Some form of output will be necessary for hardcopies. Drivers will be in place for a graphics printer, a color printer, and a plotter.

The preliminary SCAD development used an IBM PC and an IBM AT, the PC had a NEC Multisync monitor with Video-7 Vega Deluxe interface, 640 kbytes of RAM, 20 Mbyte hard disk and 360 kbyte floppy, an Epson RX80 printer and a Mouse systems PC Mouse. The IBM ATs had a CGA monitor, 640 kbytes of RAM, 20 Mbyte hard disk and hi and lo density floppy disk drives (360 Kbyte and 1.2 Mbyte), math coprocessor, IBM 5182 color printer, Hitachi Tiger Pad digitizer, HP model 7475 and Houston model DMP-52 plotters.

The PC configuration is recommended as the minimal configuration to use with SCAD while a 80386 based PC should perform much faster. Since graphics is viewed as a very important part of this software, an additional graphics component may be added during the second phase of the development; however, the desire to make the software useable on the most basic PC will also be a driving factor.

3.0   BACKGROUND

3.1   Source

SCAD deals with the development of near UV, visible and infrared radiation measurement systems giving spatial, spectral, and/or temporal information. The objective of these systems is to determine the nature of the radiation being generated by a source (or target). The types of targets to be detected, located or identified by the system are those encountered during the observation of the Earth's land surface from space. The radiation collected by the sensor may be emitted, reflected or scattered from an object located at ground level or by the intervening atmosphere. A typical example would be farmland covered by partial clouds. Emphasis will be placed with infrared sources and sensors during the preliminary stages of development, but the visible and UV will be addressed thoroughly in SCAD.

This section contains a discussion of sources. It includes a brief review of radiation theory and the nomenclature of radiation sources is presented. Discussions will include items which must be considered in instrumentation development such as back grounds and atmospheric phenomena, as well as target peculiarities.
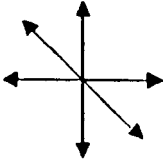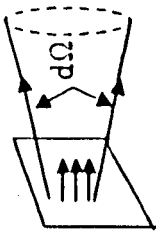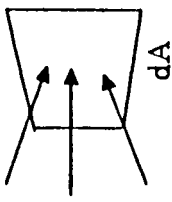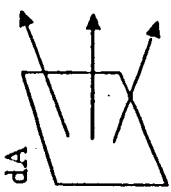
3.1.1   Source Nomenclature

Table 1 presents the names, symbols and units of the source related quantities of interest within this volume. Table 1 is a subset of the symbols and abbreviations included in Appendix I which should summarize all used in this document. The most often used spectroradiometric quantities are spectral radiance, spectral radiant intensity, spectral radiant emittance and spectral irradiance. The concept of spectral irradiance is associated with the sensor while the other quantities are associated with the source of radiation. Table 2 summarizes these spectroradiometric quantities, their symbols, as used in SCAD, and includes an illustration for further clarity.

A source is said to produce a spectral radiant energy, W_λ, at a rate called the spectral radiant power or flux, $\emptyset_\lambda$. A practical unit of spectral radiant energy is the watt-second per micron, therefore the unit for the spectral radiant flux is the watt per micron. The manner in which the flux leaves the source can be further qualified by specifying the quotient of the radiant flux, $d\emptyset_\lambda$, leaving in a given direction divided by the solid angle element, dA, covered by the radiation. This quotient is called the radiant intensity, I_λ, of the source. Since the unit of solid angle is steradians the unit of radiant intensity is the watt per steradian-micron. This quantity is valid only for point sources. It is presumed applicable to extended sources if the entire source can be included within the instantaneous field of view of the viewing instrument. To further clarify the manner in which the source produces the radiation two other quantities, the spectral radiant emittance M, and the spectral radiance L, are also used. The spectral radiant emittance is the ratio of the radiant flux emitted from the surface element, $d\emptyset_\lambda$, divided by the area of the surface element, dA. Therefore, the spectral radiant emittance is the density of the radiant flux per unit area with units watts per square centimeter-micron. Spectral radiance is a source function relating the flux radiated from a unit area into a unit solid angle. The radiance is the quotient of the radiant intensity which passes through a surface element, dA, in a given direction divided by the projection, dAcos(θ), of the surface element, where θ is

TABLE 1

SOURCE NOMENCLATURE

QUANTITY	SYMBOL	UNITS
Area	A	cm^2
Solid Angle	Ω	steradian(sr)
Power	Q	watt
Irradiance	E	$watt-cm^{-2}$
Radiant Intensity	I	$watt-sr^{-1}$
Radiance	L	$watt-cm^{-2}sr^{-1}$
Emittance	M	$watt-cm^{-2}$
Spectral Power	Q_λ	$watt-\mu m^{-1}$
Spectral Power	Q_ν	$watt-(cm^{-1})$
Spectral Irradiance	E_λ	$watt-cm^{-2}-\mu m^{-1}$
Spectral Irradiance	E_ν	$watt-cm^{-2}-(cm^{-1})$
Spectral Radiant Intensity	I_λ	$watt-sr^{-1}-\mu m^{-1}$
Spectral Radiant Intensity	I_ν	$watt-sr^{-1}-(cm^{-1})$
Spectral Radiance	L_λ	$watt-sr^{-1}-cm^{-2}-\mu m^{-1}$
Spectral Radiance	L_ν	$watt-sr^{-1}-cm^{-2}-(cm^{-1})$
Spectral Emittance	M_λ	$watt-cm^{-2}-\mu m^{-1}$
Spectral Emittance	M_ν	$watt-cm^{-2}-(cm^{-1})$
Transmission	τ	%
Reflectivity	Γ	%
Absorptivity	α	%
Emissivity	ϵ	%

Name	Symbol	Dimension	Units	
Spectral Radiant Power	Φ_λ	$\dfrac{\text{Power}}{\text{Wavelength} (= \lambda)}$	$\dfrac{\text{Watt}}{\mu m}$	$\Phi_\lambda = \dfrac{d^2w}{dtd\lambda}$ W = Radiant Energy
Spectral Radiance	L_λ	$\dfrac{\text{Power}}{\text{Area} \times \text{Solid Angle} \times \lambda}$	$\dfrac{\text{Watt}}{cm^2 \cdot sr \cdot \mu m}$	$L_\lambda = \dfrac{d^2J\lambda}{dA \cdot \cos\phi d\lambda}$ or $\dfrac{d^3J\lambda}{dA \cdot \cos\phi d\Omega d\lambda}$
Spectral Radiant Intensity	I_λ	$\dfrac{\text{Power}}{\text{Solid Angle} \times \lambda}$	$\dfrac{\text{Watt}}{sr \cdot \mu m}$	$I_\lambda = \dfrac{d^2\phi\lambda}{d\Omega d\lambda}$
Spectral Irradiance	E_λ	$\dfrac{\text{Power}}{\text{Area} \times \lambda}$	$\dfrac{\text{Watt}}{cm^2 \mu m}$	$E_\lambda = \dfrac{d^2\phi\lambda}{dAd\lambda}$
Spectral Excitance	M_λ	$\dfrac{\text{Power}}{\text{Area} \times \lambda}$	$\dfrac{\text{Watt}}{cm^2 \mu m}$	$M_\lambda = \dfrac{d^2\phi\lambda}{dad\lambda}$

RADIOMETRIC UNITS

TABLE 2
Page 10

the angle between the direction of radiation and the normal to the surface. The spectral radiance has units watts per steradian-square centimenter-micron. Both the spectral radiant emittance and spectral radiance are applicable to extended sources.

The quantities transmission, τ, reflectivity, ρ, absorptivity, α, and emissivity, ϵ, are ratios. Transmissivity is the ratio of transmitted radiation to incident radiation. For example transmissivity is the ratio of spectral radiant intensity transmitted through a medium to the spectral radiant intensity incident upon that media. (The example could have been with either spectral radiances or spectral irradiances instead of intensity.) The reflectivity is the ratio of reflected radiation from an object to the radiation incident upon the object. The absorptivity is the ratio of radiation absorbed by a medium to the radiation incident upon it. Emissivity is the ratio of emitted radiation from an object to the radiation emitted from a blackbody at the same temperature.

Several observations can be made concerning these quantities. First since incident radiation must be either reflected, transmitted or absorbed it follows that

$$\alpha + \rho + \tau = 1.$$

Kirchoff's law states that with certain restrictions (see Siegel and Howell's Thermal Radiation Heat Transfer (Ref. 4))

$$\epsilon = \alpha \quad \text{so that}$$

$$\epsilon + \rho + \tau = 1.$$

Therefore, for opaque objects with $\tau = 0$

$$\epsilon + \rho = 1$$

and for a gaseous medium where $\rho \sim 0$

$$\epsilon + \tau = 1$$

and for a blackbody where $\alpha = \epsilon = 1$

$$\rho = \tau = 0.$$

One other issue must be considered in this nomenclature section. At times the point of view will switch between wavelength and wavenumbers. The wavenumber is defined as the

number of periods of an electromagnetic wave occurring in
one centimeter. The wavenumber, σ, is related to wavelength,
λ, as

$$\sigma = 10,000 / \lambda$$

where σ has units cm-1 and λ has units microns. It is
important to realize that the functional forms of X_λ and X_σ
are different. This is due to the fact that the ratio of the
size of a unit wavenumber interval to a unit wavelength
interval is a function of wavelength. This is apparent since
the derivative of λ is

$$d\lambda / d\sigma = 10,000 \; \sigma^{-2} \qquad .$$

'This fact must be remembered when converting   or
examining spectral density as functions of wavelength of
wavenumber. Fig. 4a and b are blackbody radiances as
functions of wavelength and wavenumber. The differences in
shapes of the two curves results from this wavelength
dependence. It should be noted that the shape change occurs
only with spectral density functions such as spectral
radiance or radiant intensity but not with the unitless
ratios such as τ, α, ϵ, or Γ. Several references which
include more general information regarding IR radiation
theory review are included in the Bibliography (Refs. 1, 2,
3, 4, 5, and 6).

1500K BLACKBODY RADIANCE
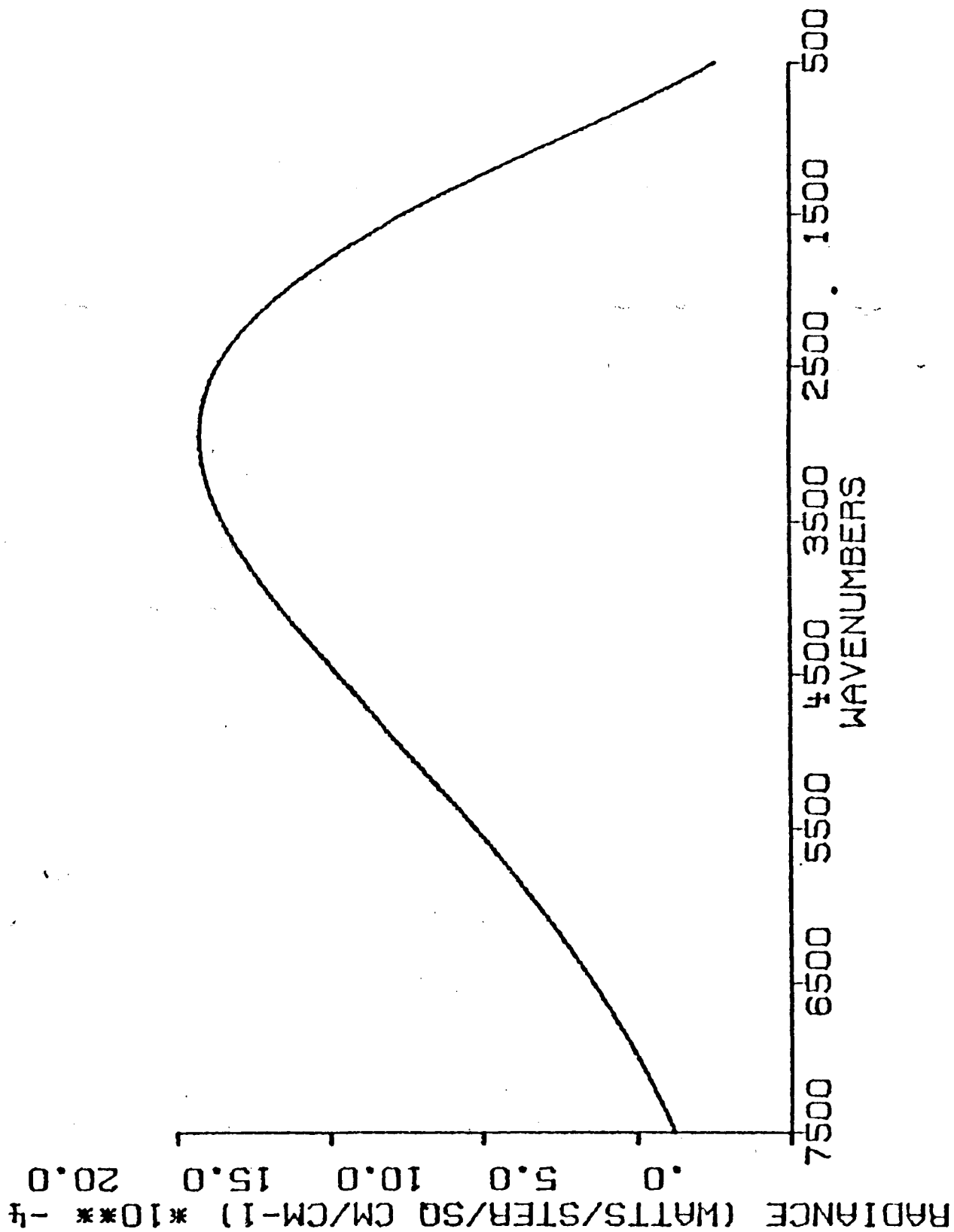
Fig. 4 a
Page 13

1500K BLACKBODY RADIANCE

Fig. 4b
Page 14
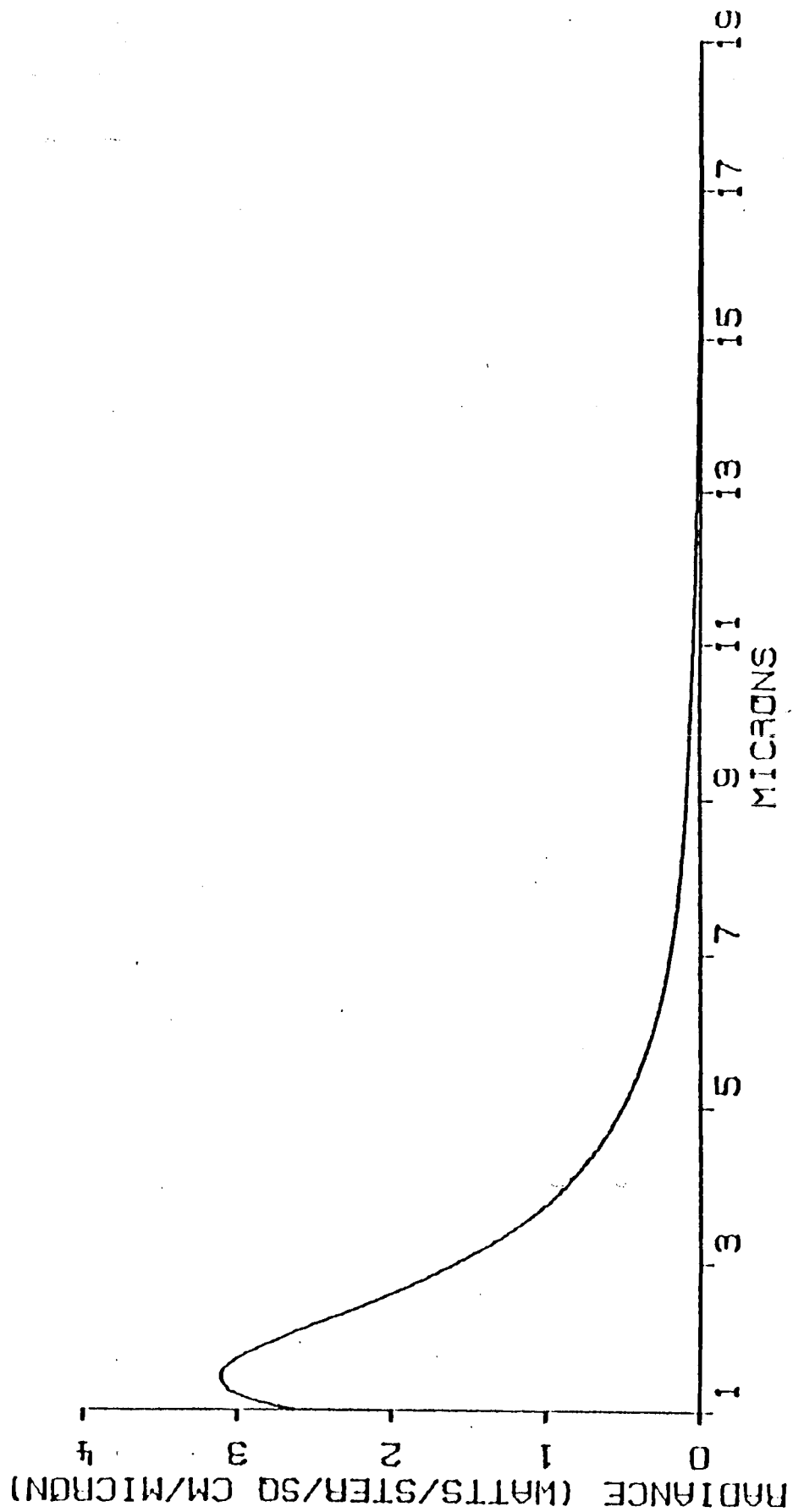
3.1.2   Typical Sources

By virtue of the molecular and atomic agitation associated with their internal energies these sources emit radiation in the form of electromagnetic waves. From Table 3 it can be seen that the emitted energy or radiation from hot gases (clouds) and thermal emitters (source of interest) will be in the infrared, visible and ultraviolet regions of the electromagnetic spectrum. Selected radiation production mechanisms for these sources are mentioned in the table.

The typical source will fall into the thermal emitter category. Thermal emitters produce radiation which can be partially described by Planck's spectral distribution of emissive power equation

$$L_\lambda = 2hc^2\epsilon_\lambda / (\lambda^5 \{exp[hc/kT_\lambda] - 1\})$$

where L_λ is the spectral radiance of the source; ϵ_λ is the spectral emissivity or measure of how well a body can radiate energy as compared to the blackbody; λ is the wavelength in microns; h is Planck's constant; k is Boltzman's constant; T is the temperature in Kelvins; and c is the speed of light. Fig. 5 shows the spectral radiance, as a function of wavelength, as calculated from the equation for a series of blackbodies (ϵ_λ =1) at different temperatures. As the figure and equation show, considerable energy is produced in the infrared.

The other major source of interest in SCAD is the sun. Although the sun will not be viewed directly, sunlight will be reflected from particles in the atmosphere, clouds, and the objects of interest on the ground. The sun resembles a 5900K blackbody with a radius of 695,000 km.

Transmission is a consideration for all the transmitting components within any optical path. This includes windows, lenses, and the like, in addition to the atmosphere. The optical properties of materials will be treated in more depth later. Presently our attention will remain with the atmospheric distortion which can alter the apparent character of a source.

The locations of the sources which will be treated in this study are almost without exception ground based with major atmospheric paths to the space based sensors. The atmospheric losses can be calculated with commonly available atmospheric models and a measured spectrum can be "corrected" to give, with a high degree of certainty, the true source spectrum.

Sources	Radiation	Wavelength, μm	Wave number, cm^{-1}	Detectors	Selected Production Mechanisms
Radioactivity	Cosmic Rays γ-Rays	10^{-6}	10^{10}	Scintillation Counters Nuclear Emulsions	① Electronic transitions in gases
Electron Bombardment, X-Ray Tubes	Hard X-Rays	10^{-5}	10^{9}		② Vibration-rotation transitions in gases; Molecular vibrations in solids and liquids; Bound electron transitions in solids
		10^{-4}	10^{8}	Ionization Detectors, Geiger tubes	
Thermal Emitters	Soft X-Rays	10^{-3}	10^{7}	Photographic Emulsions	
		10^{-2}	10^{6}		
Flames	Ultraviolet	10^{-1}	10^{5}	Photoelectric Devices	
Gas Discharges Lasers, Arcs, Sparks, Plasmas	Visible	1	10^{4}	Thermal Devices	
	Infrared	10^{1}	10^{3}		
		10^{2}	10^{2}	Photoconductive Devices	
		10^{3}	10		
Electromagnetic Generators	Microwave	10^{4}	1	Electromagnetic Detectors	③ Rotation transitions in gases; Lattice vibrations in solids
		10^{5}	0.1		

TYPICAL RADIATION SOURCES, TYPES, SPECTRAL RANGE, AND APPROPRIATE DETECTOR

TABLE 3
Page 16
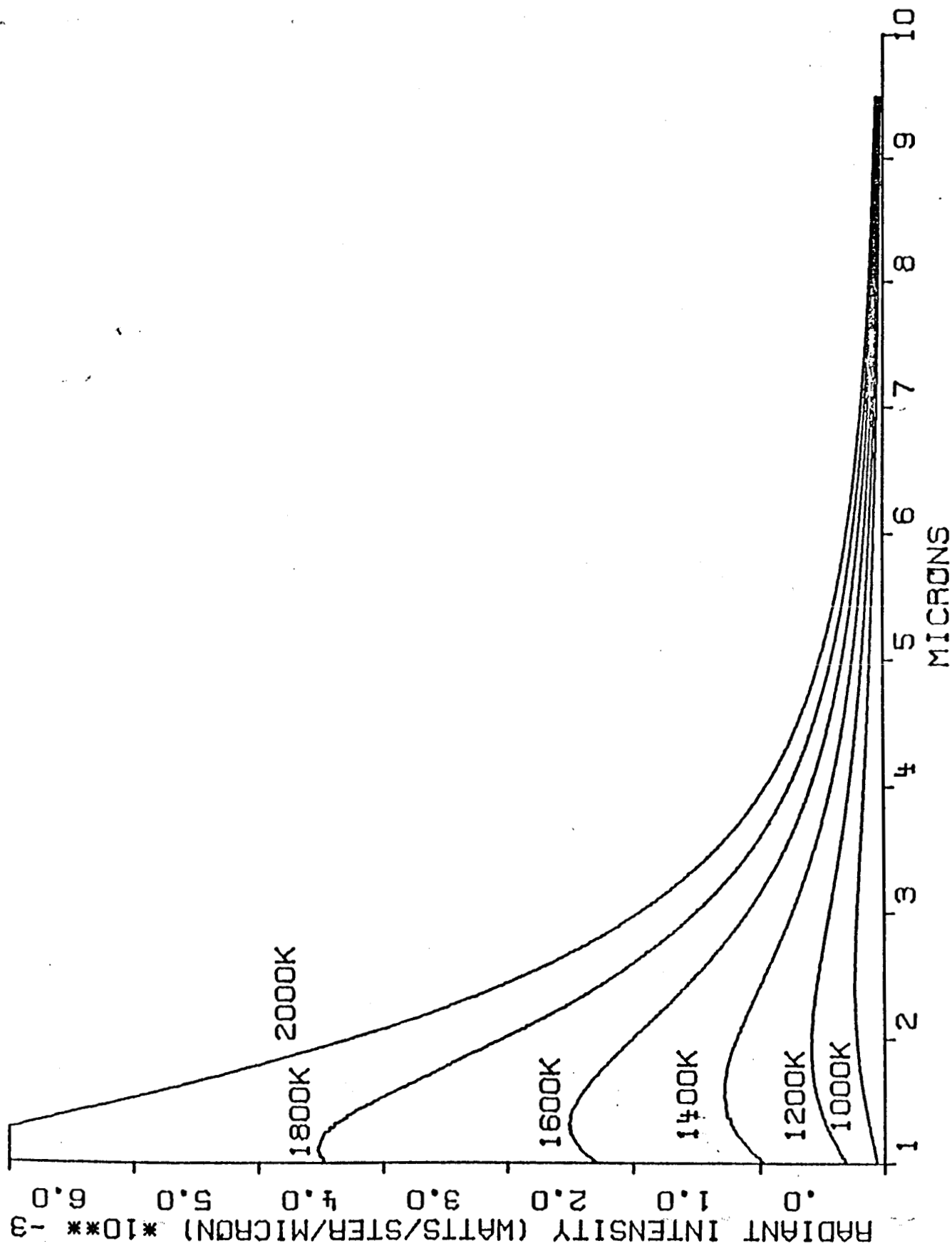
BLACKBODY RADIANCE AT SEVERAL TEMPERATURES

Fig. 5
Page 17

Another area which must be remembered and considered is the target background. The background is any radiation additional to the source radiation which can confuse the source measurement. The background is therefore just another, albeit unwanted, source within the field of view. For imaging systems, background problems are reduced over nonimaging systems. This is due to the fact that an imaging system provides spatial discrimination for objects, such as source and background within its field of view. There are, however, additional background problems which even imaging systems do not resolve. One example is the reflection of radiation from something located behind a semitransparent object. The importance of considering the background in any measurement cannot be overstated.

The variation of a source as a function of time is another critically important factor. With space based sensors operating in a swept field mode, the target being viewed at one instant in time may be quite different than that viewed in the next successive instant of time. Therefore, the radiation can vary dramatically with time and it is important that a measurement system have an adequate response time to deal with the fluctuations of the source.

From the preceeding it should be clear that the source radiance, L, can be expressed as a function of spatial position (x,y), time (t), as well as spectral frequency (σ) or wavelength ( ). With each of the independent variables there are associated problems or considerations which can not be overlooked in the development of a measurement system. After the list of previously mentioned items has been resolved, the more general considerations such as the dimensions of the source and the dynamic range of the radiances at different positions and wavelengths must then be considered. It is interesting to note that most applications will offer new and difficult problems which must be overcome for a successful measurement.

3.2   Instrumentation

After having surveyed the source nomenclature and the kinds of sources of current interest it is important to review the typical infrared measurement systems in order to illustrate both the current state of the technology and to demonstrate the value of the subject system. The infrared instrumentation system can assume numerous forms depending upon the measured quantity. Fig. 6 illustrates the basic measurement system. In the basic system, a sensor comprised of optical components, detector (or radiation transducer)
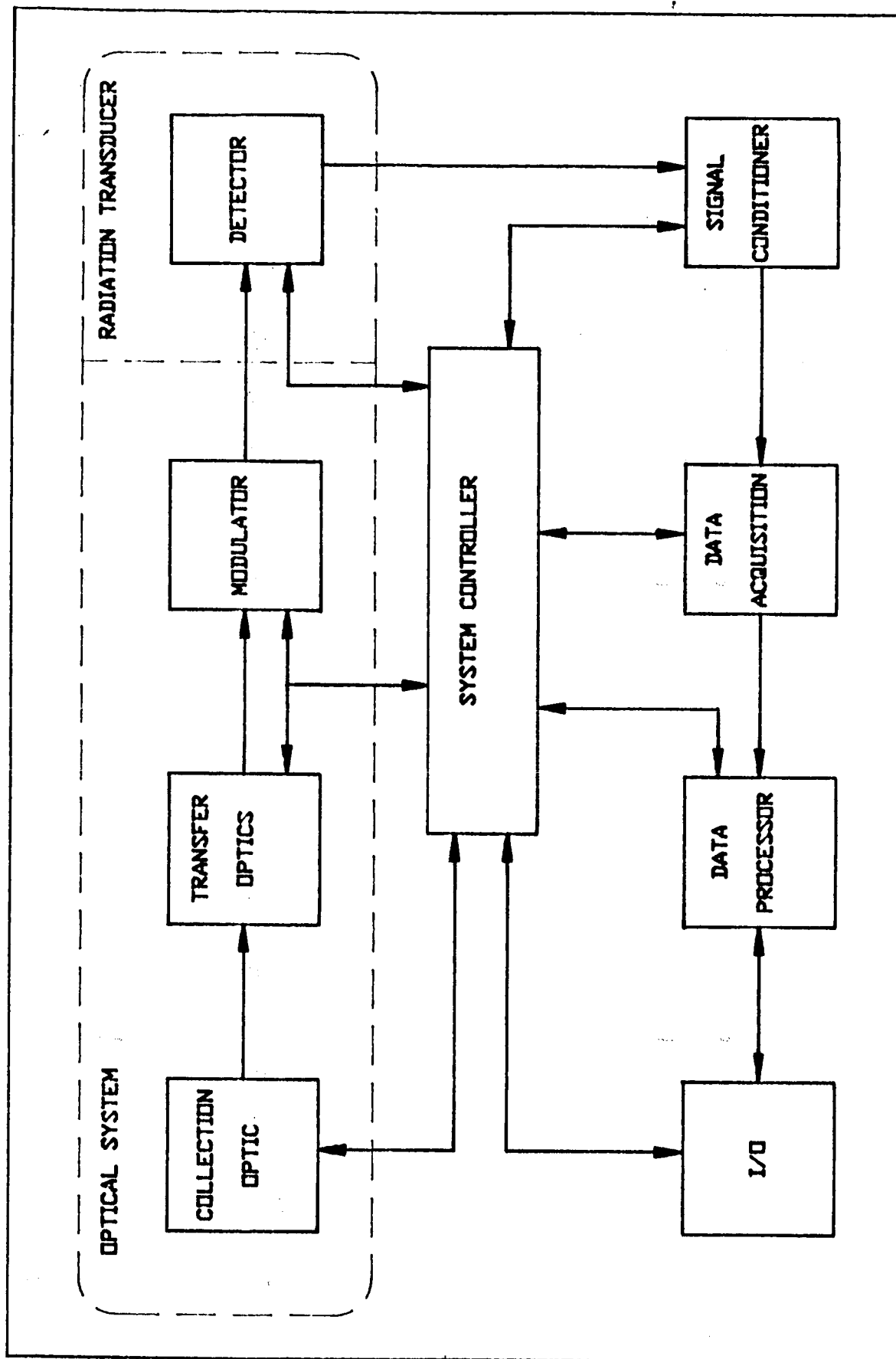
ELEMENT OF AN OPTICAL MEASUREMENT SYSTEM

Fig. 6

and associated signal and control electronics generate a signal which is passed to a data handling system for analysis. Several of the components of the system will be individually discussed, with the more popular systems currently in use being used as examples.

3.2.1   Optical System

The first subsystem, following the source and any intervening transmitting media, is the optical system. The optical system includes the collection optic, transfer optics, optical modulator (optional) and perhaps additional apertures or stops. Although at times the optical system contains many elements its function can be depicted in the simple form shown in Fig. 7a. The purpose of the optical system, shown schematically in Fig. 7b, is to collect and reshape wavefronts to irradiate the image plane (detector). Since the nomenclature related to optics is so broad and diverse a complete listing of the jargon of this field will not be attempted. The nomenclature required to understand the optical systems which are to be discussed will be presented within the description of a basic optical system. The text Optics by Hecht and Zajac (Ref. 7) is suggested as a reasonable source of the nomenclature of this field. A number of texts and articles are mentioned in the Bibliography pertaining to optical systems (Refs. 8, 9, 10, 11, 12, 13, and 14).

For the radiometric sensors under discussion it is important to have a measure of how effective the optics are in collecting the radiation and to have an accurate knowledge of the size and location of the radiation source which the optics are viewing. These light gathering and field of view properties are defined by the effective stops and pupils and the spectral transmissivity of the subsystem. The quality of the image can also be degraded from an ideal scaled reproduction of the source by aberrations introduced by the nonideal character of the lenses and mirrors used in the sensor's optics.

In all optical systems there are apertures which limit the passage of radiation through the system. These apertures include the edges of lenses or mirrors, the edges of detectors and the clear diameters of baffles or diaphragms introduced specifically to limit the image irradiance. The aperture stop is that element in the optical train which limits the angular size of the cone of radiation accepted by the system (see Fig. 8). The image of the aperture stop as viewed from the source plane is called

FOCAL
LENGTH

• F

a) BASIC SYSTEM

APERTURE STOP   FIELD STOP

b) FUNCTION OF SYSTEM
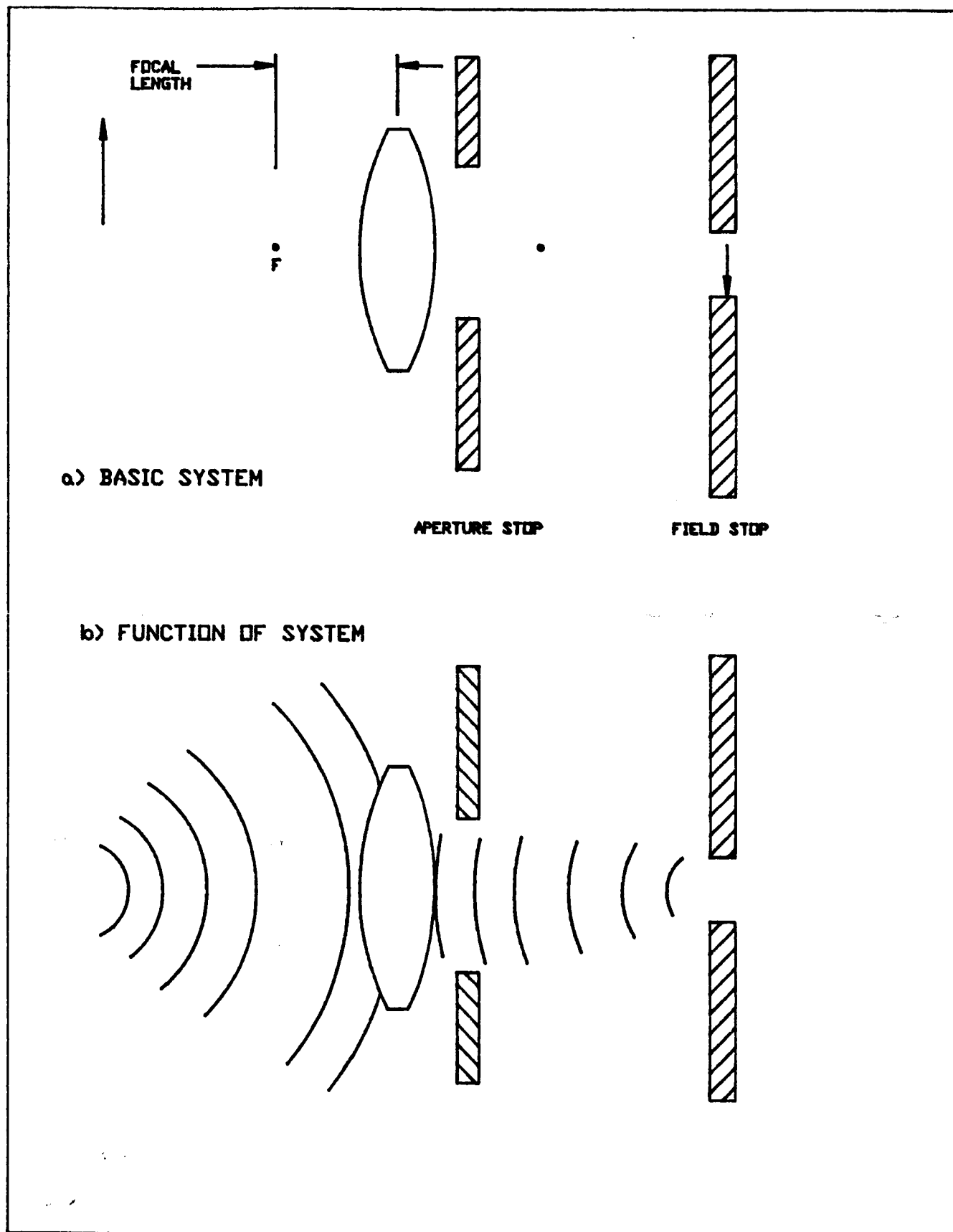
THE BASIC OPTICAL SYSTEM

FIG. 7
PAGE 21
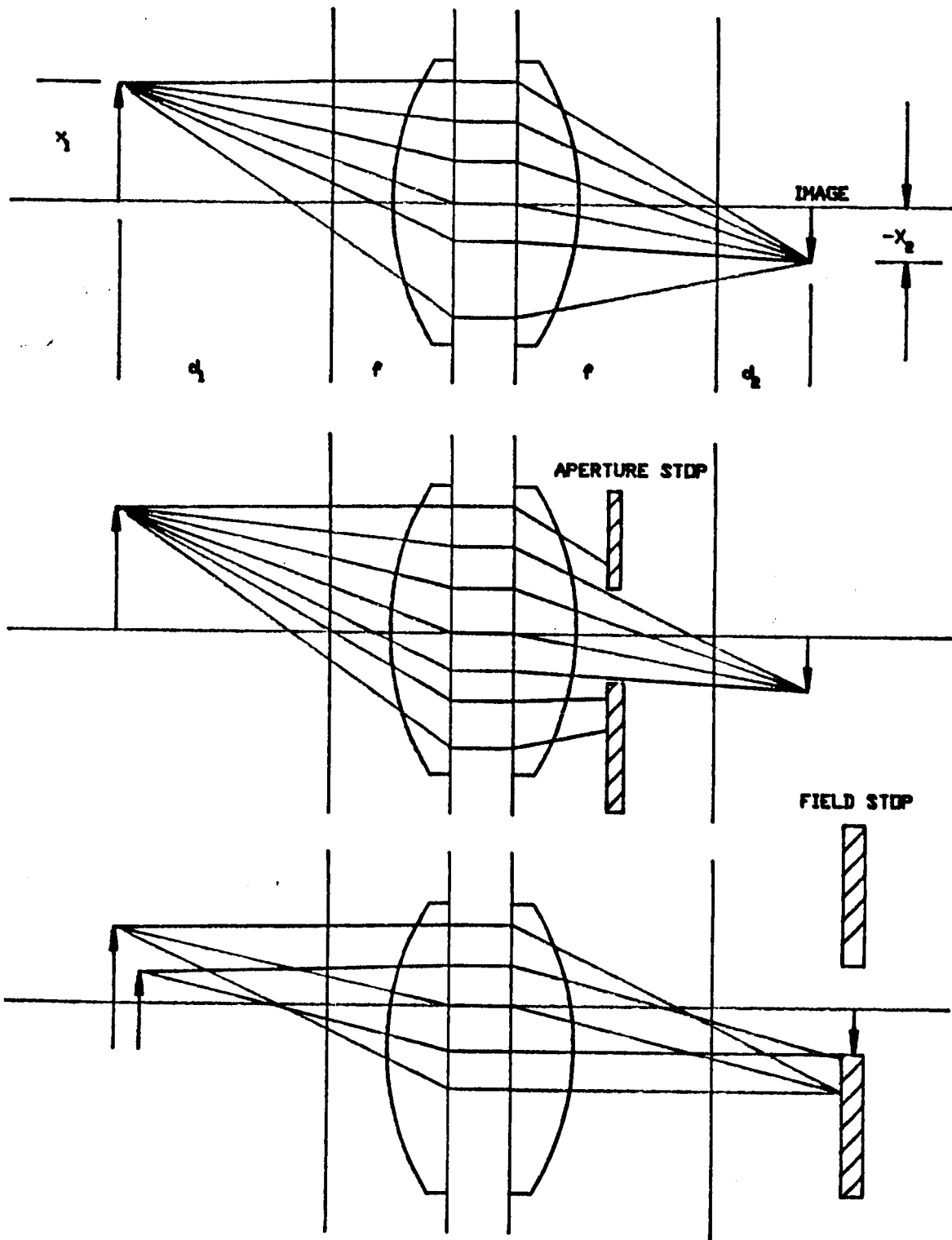
THE EFFECT OF APERTURE AND FIELD STOPS

FIG. 8

the entrance pupil.   The entrance pupil is located in the
plane containing the intersection of the line coincident
with the chief ray (a ray from an off-axis point on the
object passing through the center of the aperture stop) as
it enters the system and the optical axis. The image of the
aperture stop as viewed from the image plane is called the
exit pupil. This pupil is located in the plane containing
the intersection of the line coincident with the chief ray
as it passes from the system and the optical axis. Fig. 9a
and 9b show examples of the aperture stop and entrance and
exit pupils. The field stop is the element in the optical
train which limits the size of the image which can be formed
by the system (i.e. defines the field of view).

Generally the light gathering power is defined not by a
schematic giving dimensions and pupil locations but rather
by the f-number or its reciprocal, the relative aperture, of
the system. The f-number is defined as the ratio of the
effective focal length to the diameter of the entrance pupil
of the system. The irradiance at the image plane then
varies inversely as the square of the f-number.

The f-number depends upon the effective focal length of
the optical components of the system. Further, the
transmissivity of the optical components also limits their
light gathering effectiveness. These properties of the
system are not influenced by the stops within the system but
rather by the shapes, combinations and materials within the
optical train. These parameters also influence the image
quality of the system. For the purposes of this study
spherical lenses and mirrors treated with paraxial
(Gaussian) theory will illustrate the necessary concepts.
The term paraxial refers to a system wherein the rays
representing the flow of the radiation make very small
angles with the optical axis and remain quite close to the
axis. The properties of the spherical mirrors or lens
encountered in this study can be adequately described by the
Gaussian lens formula (which has the identical form of the
spherical mirror formula)

$$1/s_o + 1/s_i = 1/f$$

and by the lens maker's formula for a thin lens

$$1/f = (n-1)[1/R_1 + 1/R_2]$$

Here s_o is the distance from the source to the optical
surface (along the optical axis); s_i is the distance from
the optical surface to the image; and f is the focal length
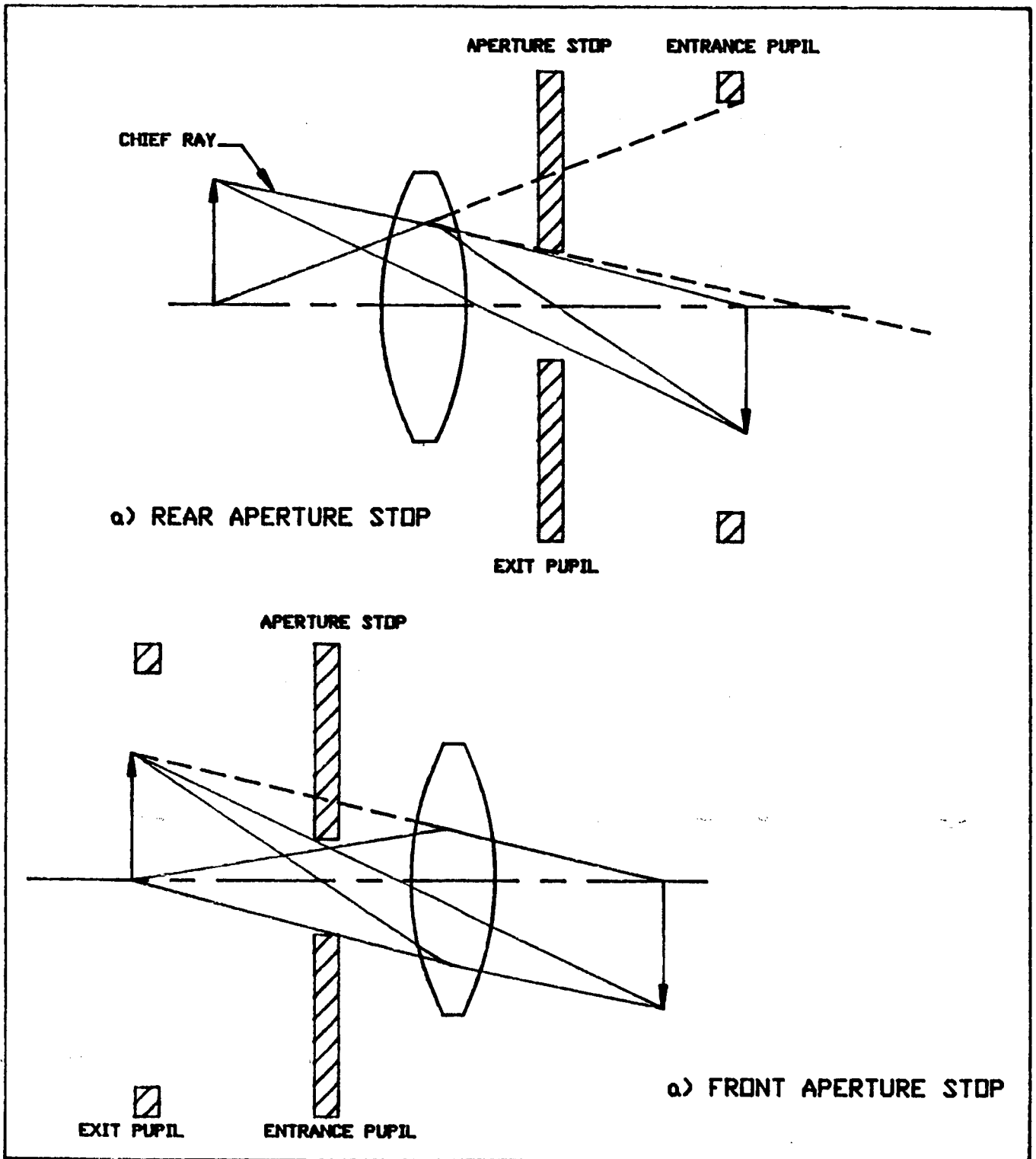
ENTRANCE AND EXIT PUPIL LOCATION

Fig. 9
page 24

of the optic. For the spherical mirror the focal length is twice the radius of curvature of the mirror. In the lens formula, the curvatures of the two sides of lens have radii R_1 and R_2 and the lens has an index of refraction n.

Combinations of lenses and/or mirrors can be reduced in pairs using the relations

$$\text{front focal length} = \frac{f_1 (d-f_2)}{d-(f_1+f_2)}$$

and

$$\text{back focal length} = \frac{f_2 (d-f_1)}{d-(f_1+f_2)}$$

where d is the separation of the two lenses and/or mirrors and f_1 and f_2 are their respective focal lengths. The front focal length is the distance from the first focal point to the first surface and the back focal length is the distance from the last surface to the second focal point. Combinations can also be treated with ray tracing techniques.

The cases of the flat lens and mirror must also be mentioned. In the case of reflection from a mirror the law of reflection is used. The law merely states that the angle of incidence of a ray of radiation upon a surface equals the angle of reflection of that ray. In the case of refraction Snell's law is used. This law states that

$$n_i \sin \theta_i = n_t \sin \theta_t$$

where n_i and n_t are the indices of refraction of the media of the incident and transmitted radiation and θ_i and θ_t are the angles of incidence and transmission of the ray of radiation.

The transmissivity of the lenses (or reflectivity if using mirrors) must be such that radiation in the desired specular region be passed through the system. Generally a high transmission over the entire spectral band width of the detector is desirable for all of the optical components except possibly the modular element components. The optical modulator sometimes is a spectral filter which limits the transmission to a narrow band of frequencies of interest. A list of some of the most commonly used materials transparent in the near ultraviolet, visible, and near infrared is presented in Table 4. Glasses used for visible optics

Table 4.   TRANSMISSION OF SOME NEAR-INFRARED OPTICAL
            MATERIALS

MATERIAL	PEAK TRANSMISSION(%)/ THICKNESS(mm)	50% TRANSMISSION POINTS ( )
FUSED SILICATE(glass)	90/2	<.5-4.2
SAPPHIRE (Al_2O_3)	93/2	<.5-7
CALCIUM FLUORIDE (CaF_2)	95/10	<.5-9.0
QUARTZ (SiO_2)	95/2	<.5-4.
MAGNESIUM FLUORIDE(MgF_2)	95/2	<.5-8.7
IRTRAN 1 (MgF_2)	93/1	.8-7.4
IRTRAN 2 (ZnSe)	74/1	.6-14.7
IRTRAN 3 (CaF)	95/1	<.5-11.5
IRTRAN 4 (ZnSe)	70/1	<.5-21.6
IRTRAN 5 (MgO)	88/1	<.5-8.8
IRTRAN 6 (CdTe)	65/1	.9-31.6
SILICON (Si)	54/2	1.2-16
GERMANIUM (Ge)	47/2	1.8-23
SODIUM CHLORIDE (NaCl)	92/2	<.5-20
THALLIUM BROMIDE-IODIDE (KRS-5)	72/5m	.56-40
POTASSIUM BROMIDE (KBR)	92/10	<.5-27
POTASSIUM CHLORIDE (KCl)	93/10	<.5-22
ARSENIC TRISULFIDE	75/2	.65-12

generally are useful to only 2.7 micron due to OH or water band absorption at 2.8 micron. Some high silica glasses or fused quartz recover transmission beyond 2.8 micron and have reasonable transmission to beyond 4 micron. Crystals such as germanium and silicon are used frequently as are other hot pressed crystals such as the Irtrans from Kodak. The transmission of a given element is usually known (this transmission characteristic is dependent upon thickness so it is peculiar to a particular optical element, not to all elements made of the same material) so it must be used as a scale factor to determine the amount of radiation passed by the given element. Combinations of elements result in an effective transmission which is the product of the transmissions of the individual elements. Optical material properties, in addition to spectral transmission, which must be considered when selecting lens materials include the index of refraction, hardness, solubility, thermal expansion and melting temperature.

Reflective optics can sometimes be used to minimize the transmission and chromatic problems associated with lenses. Caution must be exercised however since specular reflectance is not necessarily uniform over a range of wavelengths. The most frequently used mirror is the front surface vacuum deposited aluminum type. It is highly reflective (reflectance greater than 95%) in the 2 to 10 micron range. Usually the aluminum surface is protected by a coating of silicon oxide which must be of the appropriate thickness to not introduce any interference losses.

A spectral filter may be used to absorb, reflect or otherwise deviate radiation of all frequencies from the optical path except the particular band of interest. In most near infrared measurement systems the filter of choice is an interference filter of the multilayer dielectric or Fabry-Perot type. In both types the bandpass phenomenon is based on interference of multiple reflected radiation. The terminology of the filter includes the passband or primary wavelength interval of transmission, the peak transmittance which is the maximum transmittance in the passband and the halfwidth which is the width of the passband at 50% peak transmission.

The phenomena of aberrations are a consequence of the shape and composition of all the optical elements. Aberrations can be lumped into two categories: chromatic and monochromatic. Chromatic aberrations cause light of different wavelengths to be brought to a focus at different locations (because of the nonuniform index of refraction as a function of wavelength of the lens). Monochromatic

aberrations cause the image to be blurred, smeared or deformed. The five primary monochromatic aberrations are coma, spherical, astigmatism, field curvature and distortion. A thorough treatment of these so called Siedel aberrations is beyond the scope of this document so the interested reader should refer to a text such as that by Born and Wolf (Ref. 9).

After having briefly summarized the properties and nomenclature of the elements making up optical systems it is interesting to examine two examples. The optical train of one of the instruments, the Agema Thermovision, is shown schematically in Fig. 10. All of the transmitting elements in the camera are germanium except the optional spectral filter. The unique character of this camera is due to the presence of the two rotating octagonal prisms. These prisms are examples of the optical modulator referred to in Fig. 6. The optical train may be examined at several different times and the function of the prisms will become obvious. The prisms at any particular time appears to the system as merely two windows, having an index of refraction of about 4, inclined with respect to the optical axis. Consequently the prisms serve to effectively shift the optical axis, remember Snell's law, with respect to time and to position different portions of the image on the field stop at different times. By correlating the prism positions and the irradiance within the field stop, an effective wide field of view image can be obtained from this basically single element small field of view instrument.

The second example is the optical system of the Block 197RS interferometer spectrometer. Fig. 11 shows the optical schematic of this instrument. Here a large reflective element is used to collect radiation which can be limited by the aperture stop. The system has a variable field of view which is selectable with the variable field stop. The unique character of this instrument is due to the presence of the Michelson type interferometer as the optical modulator.

SELECTABLE FILTER/APERATURE WHEEL

COLLIMATION LENS

DRIVE MOTOR

LENS

LIQUID NITROGEN COOLANT

VERTICAL SCANNING PRISM

DEWAR FLASK

DRIVE MOTOR

TRANSFER OPTICS

HORIZONTAL SCANNING PRISM

INFRARED DETECTOR

IR CAMERA SCHEMATIC

Fig. 10

ORIGINAL PAGE IS
OF POOR QUALITY

WHITE LIGHT DETECTOR

LASER DETECTOR

FOLDING MIRROR M2

FOLDING MIRROR M1

FOLDING MIRROR M3

WHITE LIGHT SOURCE

LASER
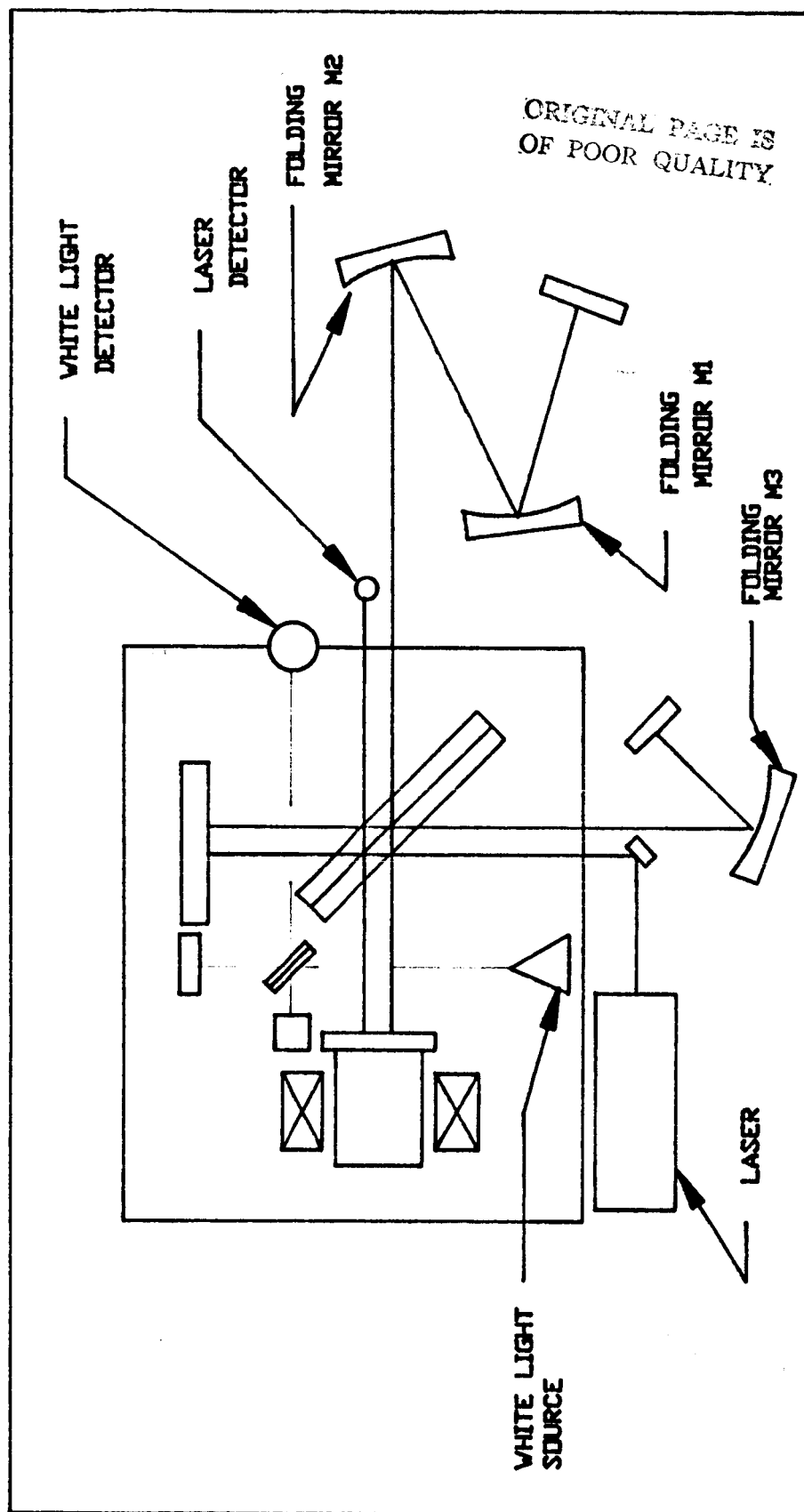
INTERFEROMETER/SPECTROMETER SCHEMATIC

FIG. 11
PAGE 30

3.2.2   Radiation Transducer

It has been shown how a portion of the radiant flux leaving a source is collected and directed to the field stop of the optical system. Following or coincident with the field stop, is the first element of the next subsystem, the radiation transducer system. Usually the edge of the first element, the detector in this system, determines the field stop. The function of the detector is to convert the irradiance incident upon it to a voltage, a current, a change in conductivity, etc. The radiation transducer system includes the detector and signal conditioning elements necessary to convert the output of the detector to voltages of appropriate levels to be handled by the next subsystem, the data acquisition system.

The radiation transducer technology is especially interesting at this point in time due to the rapid developments going on in both the detector and electronics areas. The past decade has seen the acceptance of integrated analog and digital electronics into the transducer systems. During the same period the detector industry has progressed in capabilities to the point that mosaics of literally hundreds of thousands of individual detectors can be manufactured in a single package. The hybrid and integrated systems incorporating detector, preamplifier and signal processing in a single package are rapidly becoming commercially available.

In discussing the radiation transducer it is convenient to separately treat the detector and electronics. It is useful to first mention the unique nomenclature of the detector; to then discuss the different types of detectors in use, with specific examples of detectors used in this study and then to separately discuss the electronics required to interface the detectors with a data handling system. The Bibliography includes numerous references which discuss the various detectors and systems mentioned in the following sections (Refs. 15 through 29).

3.2.2.1 Detector Nomenclature

Numerous figures of merit, operating characteristics and other constraints must be considered when matching detectors and applications. The most often used figures of merit for infrared detectors are the responsivity, the noise equivalent power, and the detectivity. Also of extreme importance in many applications is the operating temperature of the detector since the requirement for cryogenic cooling can sometimes not be met. Additional factors which also must be considered are spectral response, size, and cost.

The responsivity, R, is the ratio between the root mean squared(rms) signal voltage (or current) and the rms incident signal power. Spectral responsivity, R or $R\sigma$, refers to a monochromatic input signal while blackbody responsivity, R_{BB}, refers to an input signal having a blackbody spectrum. Typical units for responsivity are volts or amperes per watt.

The noise equivalent power, NEP, is the value of incident rms signal power for a given radiation source, bandwidth, and chopping frequency required to produce an rms signal to noise ratio of unity. The NEP is a measure of the minimum power which can be detected. The NEP is given by

$$NEP = \frac{H_d \; A \; N}{S \sqrt{f}} \qquad (watts/\sqrt{Hz})$$

where H_d is the irradiance on the detector, A is the detector surface area, S, is the voltage developed, N is the noise voltage developed by the detector, and f is the noise bandwidth used in measuring N.

Since most detectors are spectrally selective the radiation source must be specified. Usually a 500K blackbody or a particular wavelength source is specified. Further, since many detectors are used with a mechanical chopper to permit the use of phase sensitive detection, for extraction of a signal from noise, it is customary to specify the chopping frequency used for the NEP measurement. For uniformity, NEP values are specified for an equivalent noise bandwidth of 1Hz.

The detectivity, D, is simply the reciprocal of NEP. A more commonly used expression is the dee-star, D*, of the detector. D* is the S/N ratio at a given source temperature and chopping frequency with an amplifier bandwidth of 1Hz for a 1cm2 detector receiving one watt of radiant power. It is therefore a normalization of the reciprocal of NEP to take into account the area and electrical bandwidth of the detector.

The detector time constant, τ, is a measure of the speed of response of a detector. This time constant indicates the responsivity of the detector as a function of modulation frequency. Knowledge of this parameter is necessary to chose an appropriate chopping rate or the applicability of a detector for a rapidly transient source. The time constant is generally defined as

$$\tau = \frac{1}{2\pi f_c}$$

where f_c is the signal frequency at which the responsivity has dropped to 70.7% of its maximum value. The detector responsivity is generally

$$R(f) = \frac{R_o}{\sqrt{1+4\pi^2 f^2 \tau^2}}$$

where $R(f)$ is the detector responsivity at f Hz, R_o is the responsivity at low frequency and f is the modulation frequency.

3.2.2.2 Detectors

A wide variety of infrared detectors is in use. At this point in the preliminary stages of the development of SCAD, the emphasis is being directed toward the infrared and consequently this discussion will be limited to infrared detectors. The most common are photoelectric detectors and thermal detectors. The thermal detectors include bolometric, thermovoltaic, pyroelectric and thermopneumatic types. The photoelectric detectors include photovoltaic, photoconductive, photomagnetic and photoemissive types. Of the different types the most unusual is probably the thermopneumatic Golay detector. The Golay detector consists of a gas cell into which radiation is allowed to enter. The radiation heats the gas, deforms the cell and causes motion of an attached mirror or alters the character of an integrated capacitor. The detectors used in this study are the pyroelectric thermal type, the photovoltaic Indium Antimonide(InSb) and the photoconductive mercury cadmium telluride (MCT or HgCdTe) types.

In thermal detectors the responsive element is sensitive to changes in its temperature, which are caused by fluctuations in the irradiance. In the bolometric type (e.g. the thermistor is an example), the electrical conductivity is the temperature related variable. In the thermovoltaic detector (for example the thermocouple), a temperature fluctuation of a junction of dissimilar metals results in a generated voltage. With the pyroelectric detector, a change in the temperature of the sensitive element results in the generation of a current proportional to the rate of change of the temperature.

The pyroelectric detector response is based on the property of some noncentrosymmetrical crystals (sometimes called ferroelectric crystals) of exhibiting an internal electric field along a certain crystal axis. A number of materials such as triglycene sulfate (TGS) and lithium

tantalate (LiTaO3) display this response. In these crystals
the electric field is produced by the polarization of
electric dipole moments. The polarization of the dipoles is
dependent upon the lattice spacing within the crystal
which is in turn proportional to the crystal temperature.
These crystals are insulating materials and electrodes may
be attached to the crystal surfaces normal to the axis of
polarization so that an electric charge will result from the
electric field. The electrodes make the detector essentially
a capacitor. Then if the electric field is perturbed by a
crystal temperature fluctuation an observable current can be
generated in an external circuit. The current is given by

$$I(t) = F(t) A\, dT/dt$$

where F(T) is the pyroelectric coefficient at tempe-
rature T, A is the electrode surface area and dT/dt is the
rate of temperature change. Since the current varies with
changes in temperature the detector is insensitive to steady
irradiance and responds only if the irradiance fluctuates.

Since the detector response is based on its thermal
condition a judicious choice of detector size, material and
substrate is required. As with any thermal detector, the
response time depends in part on the heat transfer rate. The
heat transfer balance is of the form

$$\emptyset = A\sigma\,(T_D{}^4 - T_w{}^4) + \frac{AK}{h}\,(T_D - T_S) + cAh\frac{dT}{dt}$$

where the expression on the left is the power being
absorbed by the detector, the first term on the right
represents heat losses due to radiation, the second term is
the conduction loss and the last term reflects the ability
of the detector to store heat according to its heat
capacity. In the equation $\emptyset$ is radiation power (watts), A is
area (cm2), σ is the Stefan-Boltzman constant (5.67×10^{-4} watt
$cm^{-2}{}^\circ K^{-4}$), K is the thermal conductance (watt/(cm$^\circ$K)), h is
the detector thickness in cm, c is the specific heat of the
detector (joules* K-1*cm-3) and t is time (sec). Generally
it is assumed that the radiation loss term is insignificant
and the expression is simplified. Then the first order
differential equation is solved to obtain the expression for
the temperature of the detector

$$T(t) = \text{Constant} + (\text{constant}) * e^{\frac{-Kt}{cAh}}$$

so that the thermal time constant, τ, is cAh/K. This
thermal behavior will influence the frequency response of

the detector unless the irradiance fluctuations are significantly faster than the time constant. For the pyroelectric detector the detector current response at frequencies below W_r $(= 1/r)$ is

$$R_{iLo} \propto \frac{WAF(T)}{K}$$

while at frequencies above

$$R_{iHI} \propto \frac{F(T)}{ch}$$

The high frequency response will be valid throughout this study.

The preceding treatment assumed the detector to be a current source with a current responsivity expressed as amperes per watt. In the context of how this mode of operation is achieved, an operational amplifier is used with the detector across its differential inputs. This configuration, see Fig. 12a, holds the voltage across the detector near zero while causing a current to flow through a feedback network. This current through the feedback generates a voltage at the amplifier output. In this case the voltage responsivity has the form

$$R_{VHI} \propto \frac{1}{W} \frac{F(T)}{\epsilon cA}$$

when W is above W_r. Here e is the dielectric constant of the detector. These current and voltage responsivities suggest a superiority of the current mode of operation. The current response is constant at frequencies somewhat higher than W_r while the voltage response is inversely related to frequency. Therefore the pyroelectric detector is generally used in the current mode.

The photoelectric detectors (sometimes called quantum detectors) are based on the internal or external photoelectric effect. The internal photoelectric effect involves the excitation of electrons to higher energy levels in the conduction band by the irradiance on the detector. Electron-hole pairs are generated, either near a semiconductor p-n junction or inside a homogenous semiconductor, which establish a voltage across the junction or change the conductivity of the semiconductor. The external photoelectric effect is more dramatic and results in the escape of "free" electrons from the irradiated substance. The irradiated substance absorbs sufficient

energy to excite electrons on the photoemissive material
sufficiently to liberate them from the material. Most
quantum detectors used in the infrared are based on the
internal effect due to the low energies associated with the
low frequency photons. As mentioned earlier the two quantum
detectors used in this study are the photovoltaic indium
antimonide type and the photoconductive mercury cadmium
telluride type.

The indium antimonide detector operating at 77K acts as
a diode that generates a current proportional to the number
of photons falling on it. A general expression for the
conversion of arriving photons to a photo current, I, in the
photovoltaic detector is

$$I \simeq q N_\eta$$

where η is the fraction of photons absorbed (quantum
efficiency), q is the electron charge and N is the average
number of incident photons arriving per unit time. This
current occurs when photons with sufficient energy to
photoexcite electrons from the valence band to the
conductive band in the detector material fall on it. The
photoexcitation can occur only when the energy associated
with the incident photon equals or exceeds the band gap of
the detector material. If the photoexcitation process takes
place, electron-hole pairs are generated either near the
p-n junction or in the bulk region where they diffuse to the
junction. Then the electrons are attracted to the positive
charge in the n-type material while the holes are attracted
to the negative charge in the p-type material. There changes
modify the equilibrium charge concentration in the junction
and if sufficient electron-hole pairs are formed, cause the
photocurrent to flow in an external circuit.

In the case of the InSb detector which has a band gap
of about 0.23 electron volts at 77K, incident radiation must
be of wavelengths less than or equal to about 5.3 microns to
be absorbed. InSb at 77K has a quantum efficiency greater
than 50 percent from 3.5 microns to greater than 5 microns
making it an excellent detector for 4.3 micron carbon
dioxide band investigations. In the short circuit mode a
typical InSb photovoltaic detector has a peak dee-star of
approximately $8*10^{10}$ cm $\sqrt{H_z}$ watt^{-1}. The short circuit
current developed is linearly related to the irradiance on
the detector over five or six orders of magnitude.

The frequency response of the photovoltaic detector is shown by the expression for photocurrent

$$I = \frac{N_q N_m \{1 - \exp(-jwT_r)\}}{jwT_r}$$

where m is the modulation index of the irradiance and T_r is the drift transit time. Therefore from the standpoint of the photoelectric phenomena alone the transit time has the dominant influence on the response of the detector. Therefore the dimension of the detector through which the carriers must travel should be as small as possible to minimize the transit time. Additionally, the associated capacitances, inductances and resistances associated with a practical diode and circuit have a strong influence on the frequency response. For the typical InSb detector mentioned earlier the dee-star is effectively constant at modulation frequencies from about 10 Hz to about 100 KHz.

The HgCdTe detector operating at 77K acts as a resistor whose value varies according to the number of photons falling on it. In this detector electrons in the valence band absorb the energy of the incident photons and are excited into free states in the conduction band. The electrons remain in the conduction band for some characteristic lifetime. Electrical conduction then takes place by the electrons in the conduction band or by the holes vacated in the valence band. The resistance varies inversely with irradiance. HgCdTe is a pseudo-binary alloy composed of the semimental HgTe and the semiconductor CdTe. This composition permits a continuously adjustable band gap of -0.3ev to 1.6ev depending upon the ratio of CdTe to HgTe. The cutoff wavelength can therefore be tailored in the near infrared range according to the equation (a rewrite of E=h)

$$\lambda c = 1.24/ E_g$$

where λc is the threshold wavelength in microns and E_g is the band gap in electron volts.

These photoconductive detectors are generally used with circuits which produce varying currents with fluctuating irradiance. In these detectors the free electron concentration, N_e, is related to the rate at which photons arrive at the detector, N, by

$$N_e = N^n \tau_e$$

where n is the fraction of photons absorbed (quantum efficiency) and e is the lifetime of the resulting excited

electrons. Although a more complex situation occurs (involving the change in hole concentration, differing lifetimes of holes and electrons, and surface versus bulk behavior), it will be omitted for brevity. The change in conductivity, δc, is then

$$\delta c = \frac{Nequ}{AL}$$

where c is the electron mobility, q is the electron charge, L is the electrode separation and A is the detector area. Then any current change, δI, for a dc biased photoconductor will be

$$\delta I = \frac{\delta cAV}{L} = \frac{nN_\tau equV}{L^2}$$

where V is the bias voltage.

The photoconductive HgCdTe detectors are capable of covering a wide portion of the near infrared spectrum in its various alloy compositions. A typical alloy has a cutoff wavelength in the vicinity of 14 micron and a peak dee-star of $2-10^{10}$ cm $\sqrt{Hz}$ W^{-1} . Generally as the cutoff wavelength is increased the dee-star is decreased.

The frequency response of the photoconductor is shown by the more complete representation of the optically induced current

$$I = \frac{nqNm_\tau uV}{L^2} \quad \frac{exp\{jtau^{-1}(w_\tau)\}}{\sqrt{1tw^2\tau^2}}$$

where m is the modulation index of the irradiance and the other parameters are as previously mentioned. As this expression shows a large τ is desirable for large current responsivity but a small τ is desirable for rapid frequency response. To obtain a flat frequency response this means the τ should be approximately equal to $(2\pi f)^{-1}$ where f is the bandwidth of operation. In the typical HgCdTe detector referred to earlier, the dee-star is effectively constant at modulation frequencies from about 10 KHz to about 300 KHz.

3.2.3   Signal Conditioning

The signal conditioning required in sensors can be very diverse. It is important that the appropriate conditioning be used or the potential of the detection system may not be fully realized. As with the field of optics this area will only be discussed cursorily. A

reasonably thorough familiarity with the nomenclature of
analog and digital electronics is assumed. Texts such as
Strobel's Chemical Instrumentation or Diefenderfer's
Principles of Electronic Instrumentation (Refs. 5 and 29)
are suggested as excellent introductions to the nomenclature
of electronic instrumentation. These types of detectors
were described in some detail; therefore, the signal
conditioning required in a typical application of these
detectors will be discussed along with as much nomenclature
as reasonable. A brief discussion will be given for arrays
of these detectors as they offer great promise in most
sensor concepts.

The first detector mentioned earlier was the
pyroelectric detector. As that discussion pointed out the
usual application finds the detector operating in the
current mode. Fig. 12a or b shows the first stage of the
signal conditioning circuit. This circuit serves to convert
the change in capacitance of the detector to a fluctuating
voltage which can be dealt with by later stages of signal
conditioning. As is typical with most electronic systems the
preamplifier provides some gain and is located near the
detector so that signals which must be transmitted
appreciable distances will be much larger than any noise
which might be introduced into the cabling. Manufacturers of
pyroelectric detectors currently include either all or a
portion of the components required for the preamplifier
within the detector package. Figs. 12a and b show two
typical detector/preamplifier circuits with the common
detector configurations.

Electrically one of the most important parameters
associated with the detector/preamplifier combination is the
electrical band width. Here it must be clearly understood
that no longer is the concern with the spectral bandwidth
which was critically important in the selection of windows,
lenses, and detector. This electrical bandwidth is simply
the range of the frequencies of the alternating current
which can flow through detector and electronics. The
electrical bandwidth is defined as the range of frequencies
within which the amplifier will respond. The frequency range
is often measured between the half power (3-dB) points on
the output response versus frequency curve for a constant
input. The band width of the signal electronics is often
tailored for various reasons through the use of electronic
filters. High and low pass filters are often employed to
remove the ever present 60 Hz noise and noise of frequencies
outside the frequency band of interest. A high pass filter
passes signals with frequencies higher than a selected
value. The low pass filter passes frequencies below a
selected cutoff value.

a) INTERNAL FET OP AMP

b) INTERNAL RESISTOR AND FET
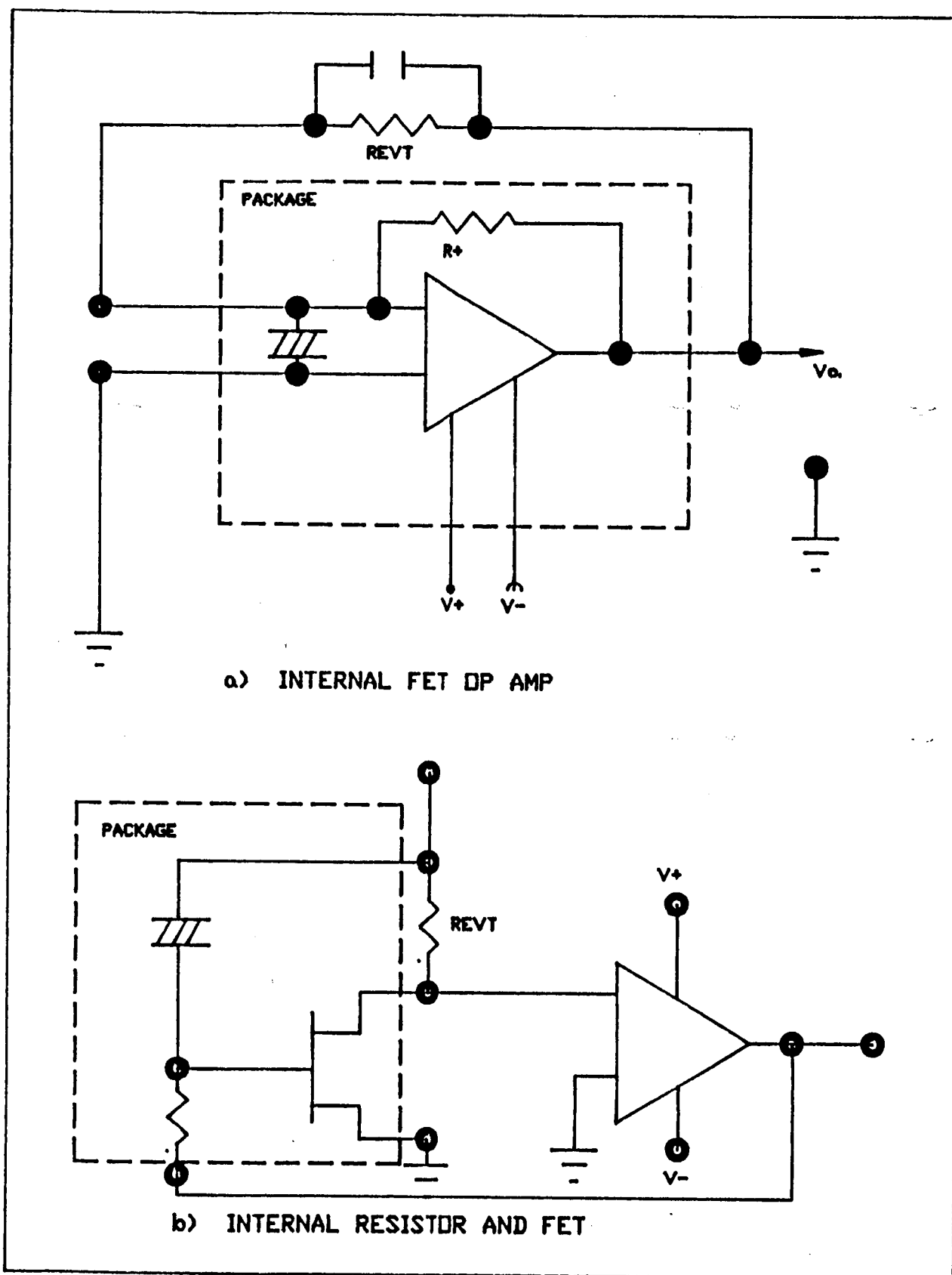
PYROELECTRIC/PREAMPLIFIER CONFIGURATIONS

FIG. 12

It is also important that the gain and noise figure, NF, of the preamplifier be adequate to assure that the S/N of the detector is not seriously degraded by the remainder of the system. Here the noise figure is defined as

$$NF = \frac{S_i/N_i}{S_o/N_o}$$

where the numerator is the signal to noise ratio of the input to an amplifier and the denominator is the S/N at the output. The NF of a detector, preamplifier, and amplifier combination is

$$NF_{Total} = NF_{DET} + \frac{(NF_p - 1)}{G_{DET}} + \frac{(NF_{AMP} - 1)}{G_{DET} \, G_p}$$

where G_{DET} is the sensitivity of the detector, and G_p is the gain of the preamplifier. From this expression it can be seen that noise figures of near unity are desirable especially in the detector and preamplifier and that high sensitivities or gains are also important. It is also apparent from the equation that noise becomes progressively less critical in those amplifier stages with gains greater than unity added beyond the preamplifier.

Another signal conditioning procedure often encountered in applications of the pyroelectric detector is the use of a type of correlation analysis known as synchronous demodulation or phase sensitive detection. This procedure which involves the use of modulated signal is well suited to the pyroelectric detector. As pointed out this detector responds to changes in irradiance and is therefore frequently used with a mechanically chopped source. The technique involves the use of a stage called a lock in amplifier. The lock in amplifier is depicted in use in an ac radiometer in Fig. 13. The lock in amplifier serves two primary roles in this application. First it serves to subtract any offset or drift associated with detector, amplifiers, and filters from the final result. Second it serves to improve the S/N of the detection system. Basically the lock-in amplifier mixes the reference signal derived from the chopper position with the detector signal. Since the signal corresponds alternately to that due to the source and that due to the back side of the chopper, the two signals are correlated. As can be seen from Fig. 13 essentially a difference in signals, which are 180 deg out of phase, is found at the output of the summing amplifier. The noise is very effectively discriminated from the output of the amplifier.
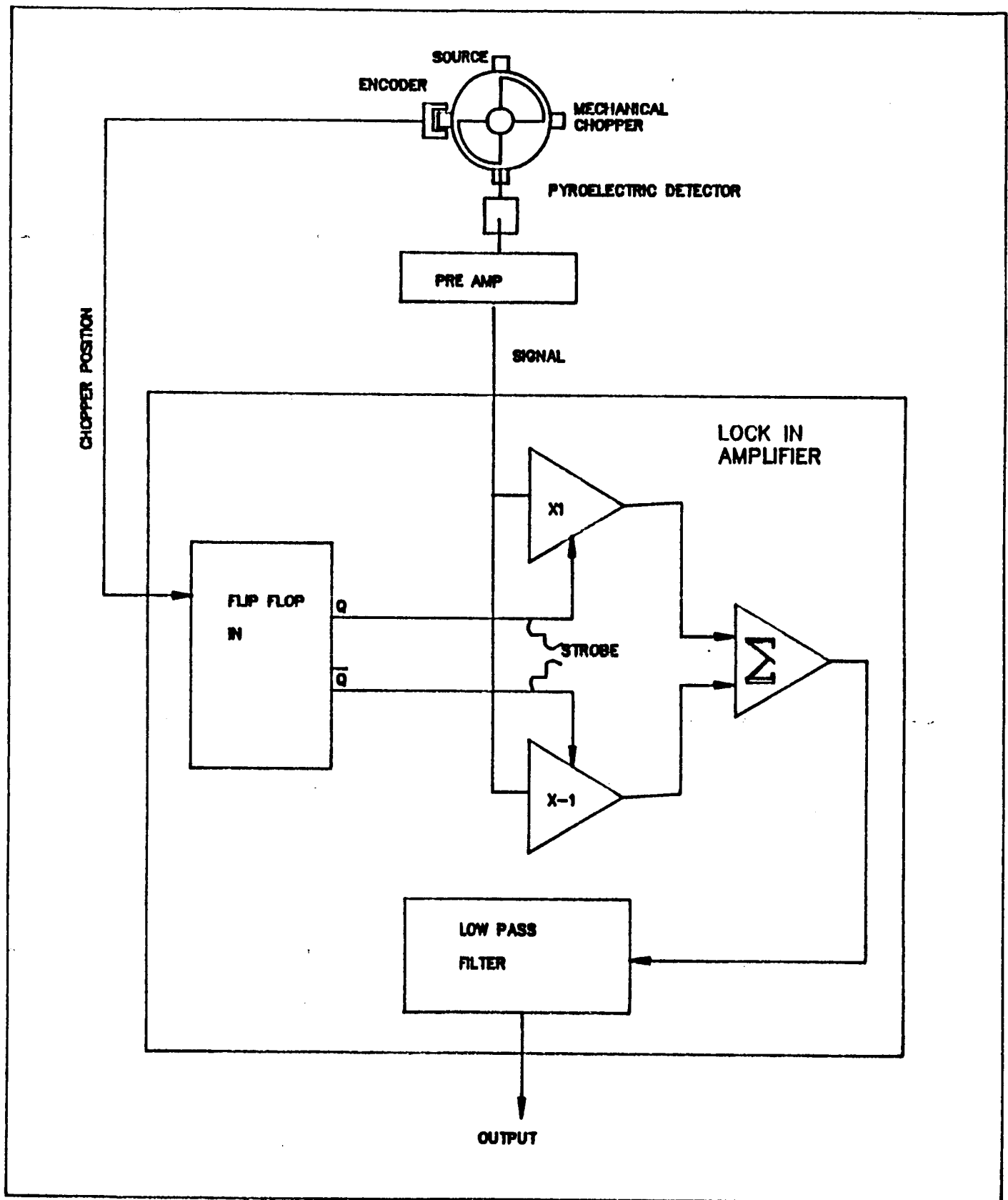
LOCK IN AMPLIFIER AND CHOPPED RADIOMETER

FIG. 13

The second detector discussed was the photovoltic InSb
type. In the short circuit mode the circuit is essentially
that shown in Fig. 12a with the pyroelectric detector
replaced by the photo voltice diode. It is important to
remember that this detector responds to the irradiance
falling on it rather than to changes in irradiance like the
pyroelectric. Therefore the InSb preamplifier may need a
bandwidth down to dc. With this exception the signal
conditioning for this detector is very similar to the
previous one.

The HgCdTe photoconductive detector requires a
different input stage to the signal conditioning circuit.
This detector's response is a small change in resistance.
To sense this change a bias voltage and a load resistor are
needed. A circuit such as shown in Fig. 14 may be used.
From the output of this stage, signal conditioning is also
very similar to that described for the pyroelectric
detector.

3.2.4   Data Acquisition

The fluctuating voltage occurring at the final stage of
the signal conditioning module in the infrared measurement
system is recorded. The act of recording the signal in a
form which is amenable to analysis is called data
acquisition. One common form of data acquisition involves
manually recording a series of voltages taken from meters or
oscilloscopes during the course of an experiment. Other
forms of data acquisition involve the use of x-y plotters,
photographs, and microdensitometers; strip charts and Gerber
scales; analog tape recorders and digital data acquisition
systems. With the exception of the digital data acquisition
system the other devices mentioned are only parts of a total
acquisition system. For example the tape recorder is only a
part of a total acquisition system because little can be
done with data in the form of magnetized strips of tape.
The analog recorder and several of the other devices
mentioned serve only to allow limitless delays in or
modifications in the timing of the acquisition process.
Since the analog tape recorder and digital systems are used
in much of the current infrared instrumentation, a summary
of the important considerations will be presented.

The analog tape recorder operation consists of moving a
magnetizable tape at constant speed across a recording head
which induces a magnetization proportional to the current in
a coil in the recording head. The signal can then be
retrieved from the tape by passing the tape over a
reproducing head where flux from the moving tape passed
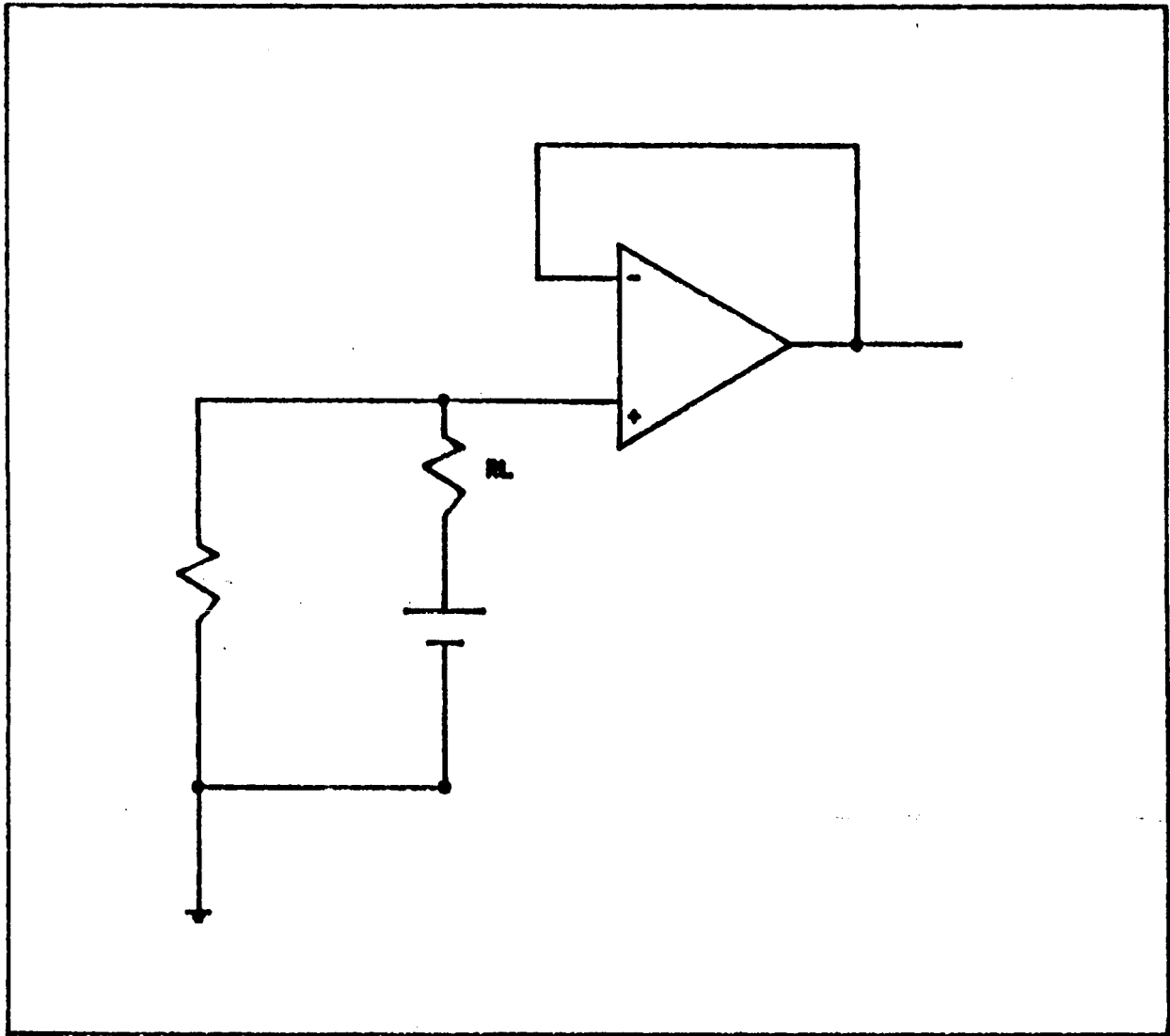
Hg Cd Te DETECTOR

Fig. 14

through a coil in the recording head in proportion to the tape magnetization. Important considerations for the use of an instrumentation tape recorder include the type recording (for example direct or FM), the tape speed, the number of channels available, the signal to noise ratio, the recorder head type and cost.

Analog tape recorders can be operated in either the direct recording mode or the frequency modulation, FM, mode. In the direct mode the voltage from the sensor is converted to a current in the record head coil so that the magnitude of input voltage corresponds to the degrees of magnetization of the tape. This mode of operation depends on the induction of a magnetization which is caused by variations of coil current and therefore can not be used for dc signals. With the FM mode a voltage controlled oscillator (VCO) biased to a frequency near the center of the bandwidth of the recorder provides the input to the record head. A large current can be used to assure a high degree of magnetization. The VCO can then be driven to produce frequencies throughout the recorder bandwidth. The FM mode is useful for frequency ranges of dc to considerably less than the highest frequency possible in the direct mode. The signal to noise ratio possible with the FM technique is approximately a factor of 5 higher than with the direct technique. The tradeoffs between the two modes basically concerns factors such as: what is an acceptable S/N, is the recording of dc necessary, what is the upper frequency limit and cost (direct electronics are cheaper).

Tape speed is also an important consideration. As the tape speed is increased the recorder bandwidth and S/N increases. The factors which must be considered with choosing a tape speed include: recorder cost increases with higher tape speed capability, the volume of tape used in a recorder operating at high speed; and of course are higher bandwidth and S/N required?

The analog recorder serves to illustrate the considerations not to be overlooked in any data recording scheme. The record must be such that the stored data can be used in the data processing stage (currently this suggests a record which can be read by a computer). The bandwidth of the recorder must be adequate to ensure acquisition of the desired data. Bandwidths much greater than necessary should be avoided since excessive volumes of data will be recorded, as well as spurious noise.

With the previous considerations in mind digital data acquisition can be examined. Digital data acquisition can

take numerous forms; however there are two basic systems: one which includes a computer and one which does not. The system that does not include a computer is generally just a data acquisition system while the other generally has additional capabilities. The limited system shown in Fig. 14 consists of a multiplexer, a sample and hold amplifier, an analog to digital converter, an interface (which includes a formatter and controller), and some form of digital storage media (for example, a digital tape recorder). The more sophisticated system contains a multiplexer, the sample and hold amplifier, the analog to digital converter, an interface to a central processing unit, high speed and bulk memory, and input/output (I/O) devices. Figure 15a is a block diagram of the limited system, and Fig. 15b is a block diagram of the system which includes a computer. Although included in the transducer subsystem, part of the signal conditioning is also shown in the acquisition system since it may be under the control of the acquisition system controller.

The signals enter the data acquisition system through the analog multiplexer. If only one signal is to be acquired this stage is omitted. The multiplexer functions as a bank of switches which allow the signals to be alternately coupled to the sample and hold amplifier. Important considerations involving this block are the programmability of the sequencer, the range of voltages permissible, switching speed (multiplexer settling time), and switching transients.

The sample and hold amplifier is the next device in the digital acquisition system. The sample and hold (S/H) cleans up and buffers the signal for the next stage which is the noise sensitive low impedance converter. Important considerations for the S/H include the acquisition and operative times along with their settling times. Fig, 16 illustrates the function of the sample and hold. In this figure, the top trace is the control signal to the S/H, the middle trace is an input to the S/H, and the bottom trace to the corresponding output of the S/H. As shown the acquisition time is the time required for the output to settle within the rated accuracy after a sample input control signal has been applied. The operative time is the delay between the time the hold control signal is applied and the actual time the circuit enters the hold mode.

Following the sample and hold amplifier, the analog to digital converter (ADC) accomplishes the translation from the analog to the digital world. The ADC may take many forms. The most popular types are the integration,

a) LIMITED SYSTEM

ANALOG BUFFER

MULTIPLEXER

SAMPLE & HOLD AMPLIFIER

ANALOG TO DIGITAL CONVERTER

BUFFER

CONTROL AND INTERFACE

DIGITAL RECORDER (e.g. Magnetic Tape)

SIGNALS

b) COMPUTERIZED SYSTEM

MULTIPLEXER

SAMPLE & HOLD AMPLIFIER

ANALOG TO DIGITAL CONVERTER

INTERFACE

COMPUTER BUS

MEMORY

CPU

DISC & TAPE INTERFACES

DIGITAL TAPES AND DISCS
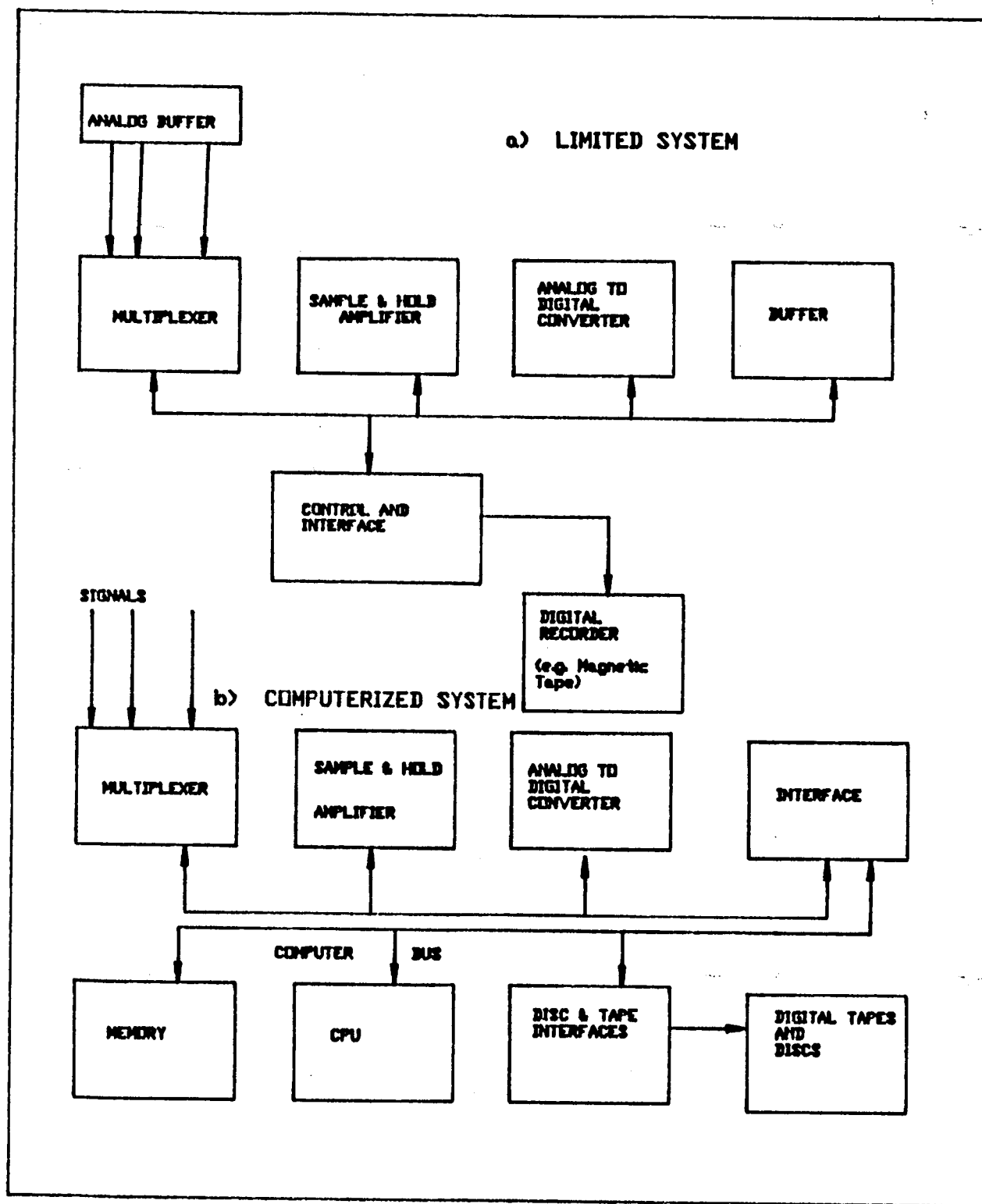
DIGITAL DATA ACQUISITION SYSTEM

Fig. 15
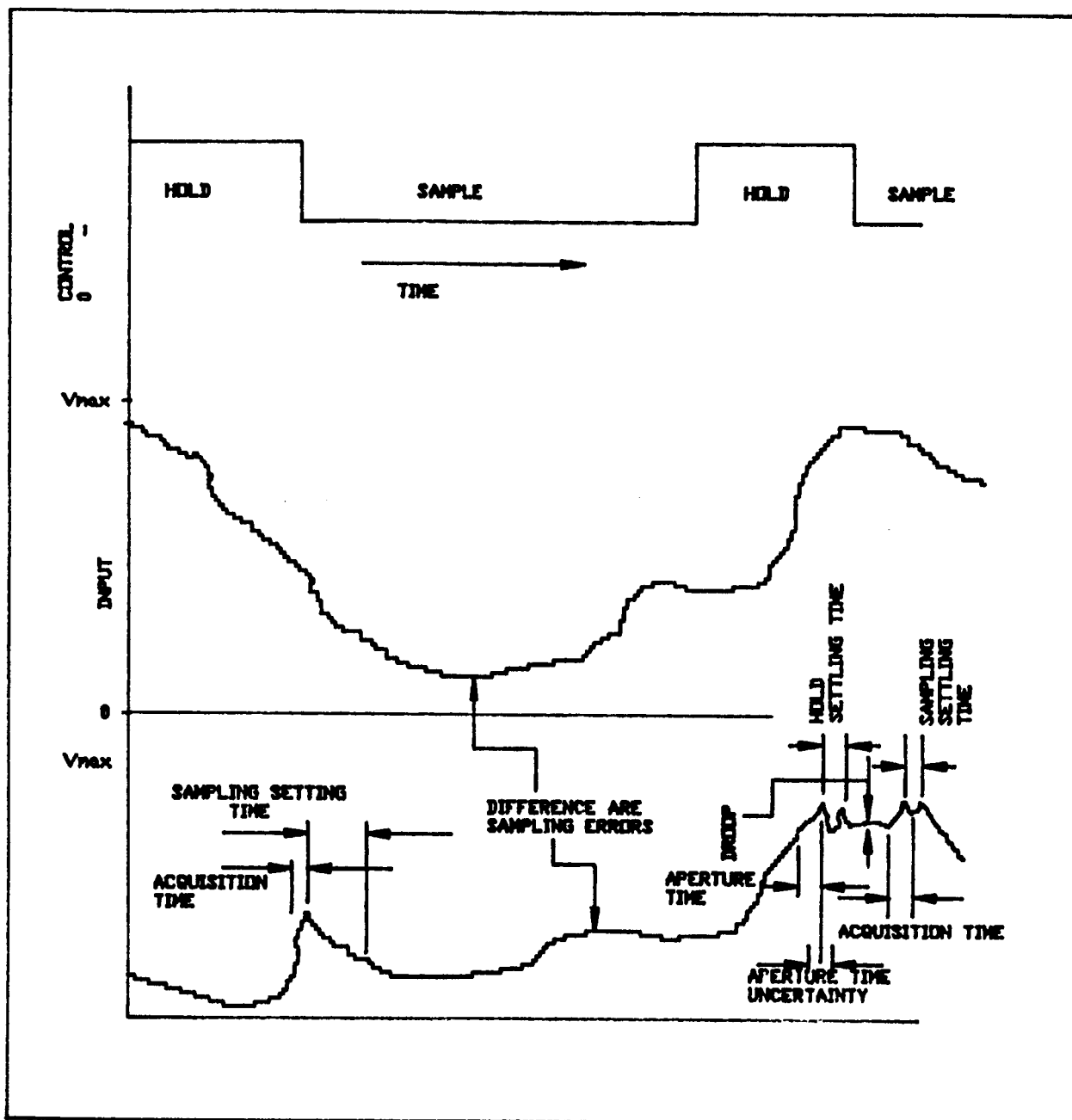
SAMPLE AND HOLD AMPLIFIER SIGNALS

FIG. 16
PAGE 48

successive approximation, tracking, multicomparator ladder
and voltage to frequency convertors. The questions arising
when applying ADC's are usually how rapidly and precisely
accurately are the conversions mode. Information theory (by
Shannon or Nyguist) suggests that the conversions should
occur at a rate at least twice the maximum frequency of
interest. The required accuracy precision of conversion is
very situation dependent. For some applications, very low
resolution may be adequate while for others one part in a
million is insufficient.

The ADC has as its input an analog voltage while as an
output it has either a single line for a serial
representation of the input or parallel lines for a parallel
representation of the input. In either case the
representation is usually a fixed point binary number which
reflects the input magnitude. From this point, this
discussion, if allowed to continue, could fill many volumes;
therefore, the interested reader should examine one of the
current texts dealing with small digital computer system.

3.2.5   Data Processing

The signal recorded by the data acquisition system is
finally retrieved and processed in some fashion to yield
that final information desired from the measurement system.
The data processing step might be as simple as the addition
of units of measure on a strip chart or as complex as the
digitization, scaling, and Fourier processing required for a
FTS. The latter is typical of data processing in today's
infrared radiation measurement systems and will be discussed
briefly in this section to provide an example of the kind of
data processing which is typical for a moderately
sophisticated sensor.

Currently data processing is synonymous with the
digital data acquisition process followed by computer aided
data manipulation and graphic presentation of results.
Subsequently hard ware is inclusive of that shown previously
in Fig 15b together with output devices such as graphics
terminals, digital plotters, or video copiers.

As an example of the digital data processing, the
treatment of data acquired from a FTS will be explained.
The flow diagram in Fig. 17 schematically presents the steps
involved. As explained previously the first step in the
digital processing process is the conditioning of the analog
signal to provide the appropriate levels and bandwidths of
signals the the digitizer. The second step is the actual
digitization of the data and transfer to computer memory.

CONDITION ANALOG DATA	APODIZE DATA
DIGITIZE ANALOG DATA	FOURIER TRANSFORM DATA
STORE DIGITAL DATA	PHASE CORRECT DATA
RETRIVE DIGITAL TEST DATA	MULTIPLY DATA BY RESPONSIVITY
RETRIVE DIGITAL BACKGROUND DATA	SCALE DATA BY GEOMETRIC FACTOR
SUBTRACT BACKGROUND DATA	STORE DATA
CALCULATE PHASE ERROR IN DATA	GRAPH DATA HARDCOPY RESULTS
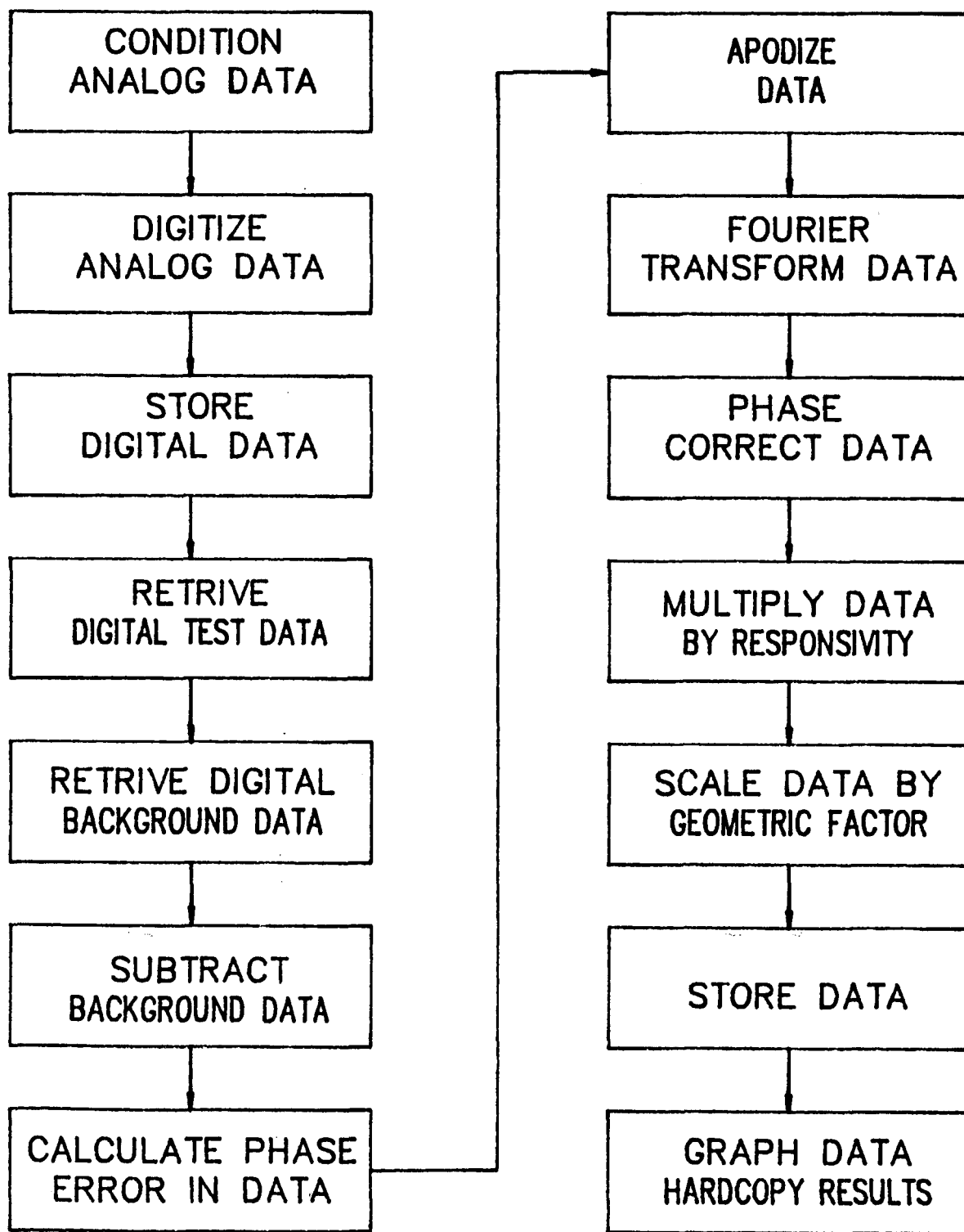
DATA PROCESSING REQUIRED FOR THE FTS SIGNAL

Fig. 17

The usual next step is the storage of that data on bulk
memory for later processing or reprocessing if required.
Therefore the next step in the process is the retrieval and
probably the reformatting of the data for subsequent file
manipulations. Usually at that time a previously created
instrument responsivity is also retrieved as the storage is
probably via some bulk media such as magnetic tape.
Assuming the data collection included the acquisition of
background data, the sixth step is the subtraction of the
background file from the data file. To this point steps are
essentially the same regardless of instrument type;
however, the next step is peculiar to the FTS. The
difference file is processed to fine phase error in the
data, and that information is stored for later use. The
data is then processed with an apodization function (this
function will be defined in a later section) and then
Fourier transformed. The phase error is then retrieved and
used to phase correct the data. The instrument response is
multiplied with the data and finally the data is scaled to
remove any geometrical factors. The final steps are data
storage and presentation.

4.0   SCAD Modules

The goal of the SCAD development is a user friendly
software to be used during the design of a space based
sensor. The SCAD software will address the areas shown in
Fig. 2. The software will be used to design a sensor system
with components as shown in Fig. 6. There is not a one to
one correspondence between sensor components and SCAD
software components. Several additional software components
are required as there are more considerations which must be
treated than there are sensor components.

The first component of SCAD addresses the problem
geometry, that is, the location of the target and the
sensor. The second component defines the source radiant
output. The third component determines atmospheric effects
and the fourth allows selection of sensor collection optic
area and the irradiance upon that optic. The fifth block of
SCAD is used to define the optical train of the sensor; the
sixth contains the detector and preamplier characteristics;
and the seventh deals with the electronics associated with
the sensor. The eighth will address data storage and data
transmission.

The SCAD modules will be designed to be used on an as
needed basis. Individual modules will be invoked during a
design session. Where practical, inputs will be permitted to
negate using modules which are of little value to a

particular   problem.   For   example,   if   atmospheric
transmission is of little interest, then that module which
calculates it may be skipped and a default or a constant
transmission loss may be specified in later modules
requiring minimal transmission information.

4.1   Geometry/Time

The geometry issues are depicted in Fig. 18.   The
inputs must contain sufficient information to define the
relative positions of the source, the sensor, and the sun.
The atmospheric conditions must be specified to the degree
that the atmospheric transmission losses and scattered solar
light can be calculated. The objective of the first SCAD
module is to either default to an appropriate set of
geometry and time parameters or to offer the user an
opportunity to input or modify them.   The intent of the
module is to provide input to the remainder of the SCAD
modules concerning the location of the target, sensor and
sun and the time of the year. The kinds of parameters
required in later modules are the sensor to target range,
the angle of the sun, and the like. A minimal set of inputs
providing adequate information for standard parameters to be
selected consists of: the target altitude, longitude, and
latitude; the sensor altitude, longitude, and latitude; and
the time of year (which includes day, hour, minute).

The module will have graphics capabilities which will
include a topographical map of the world on which sensor and
source locations can be chosen by a mouse driven cursor. The
module will permit zooming for accurate positioning of the
cursor and will provide output of the chosen geometry. Time
will be entered in terms of Zulu or from any selected time
zone.

The algorithms for extracting the appropriate
information from these inputs are straight forward and can
be implemented with high level languages such as FORTRAN, C,
or BASIC. The choice of an appropriate software to provide
the desired graphics is the most significant issue for this
module. At this point another major decision remains to be
made of whether to implement this and the next several
modules using components or to adapt an existing software
which contains a significant number of required features to
address this problem. A software package developed for DOD
by Aerodyne Research, Inc. named SPIRITS includes a number
of features (see Table 5 for a summary of sources modeled by
Spirits) which are desirable for SCAD. The SPIRITS software
was developed for larger computers, but is currently being
imported to the PC. The SPIRITS software is presently
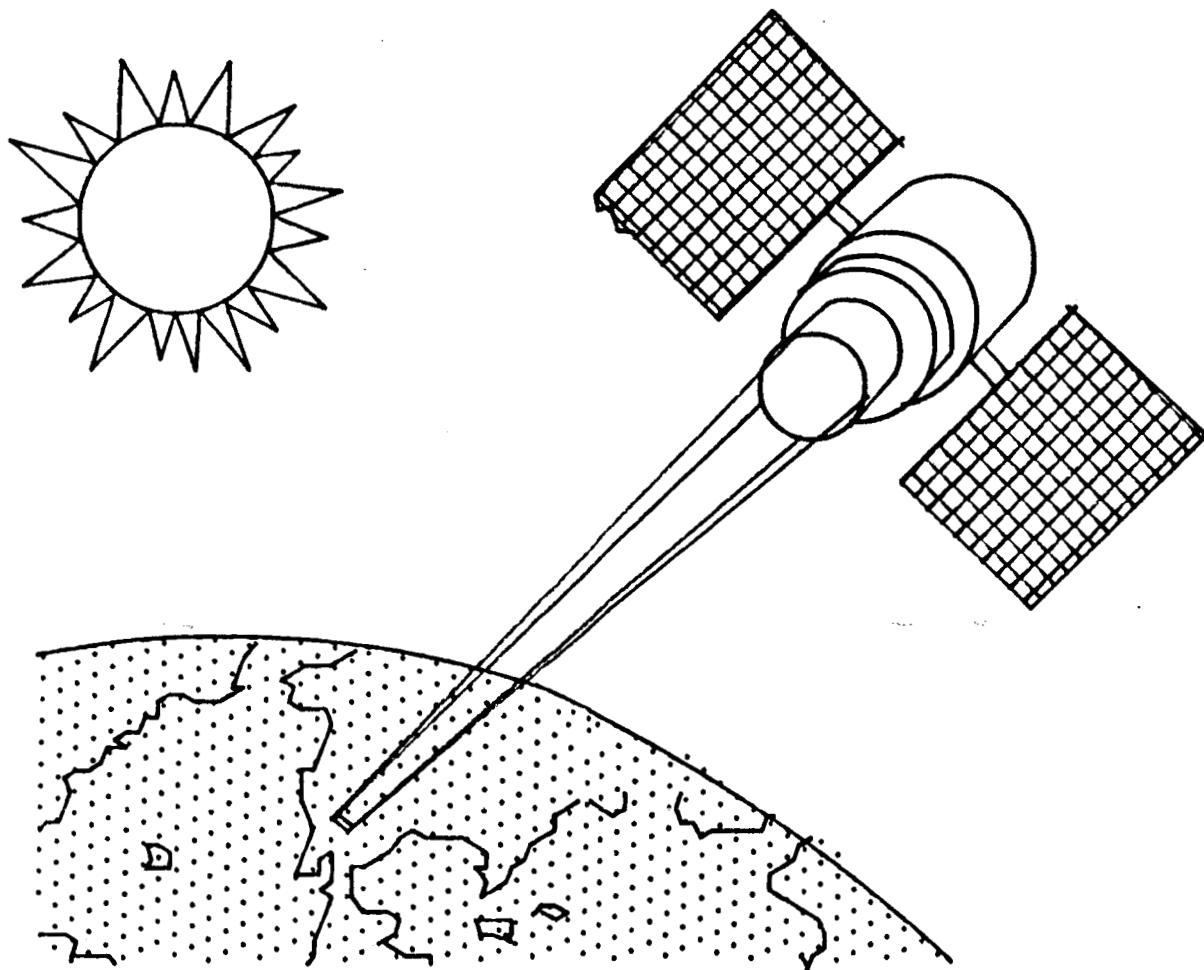
GEOMETRY/TIME

SENSOR ALTITUDE   TARGET LONGITUDE
TARGET ALTITUDE   TARGET LATITUDE

SENSOR LATITUDE   TIME
SENSOR LATITUDE

COMPATIBLE WITH ACAD GRAPHICS

Fig. 18

Table 5

Phenomena	Comments
Exhaust plume emission and radiance	Precomputed; currently using SPF1 and NEXTARC; transmission and obscuration included
Engine hot parts	Transmitted through plume
Target emission	Aerodynamic and solar heating; directional emitance; engine heating
Reflected sun, earth, and skyshine	Bidirectional reflectance
Internal heat sources	Semi-empirical
Atmospheric transmission and radiance	LOWTRAN6; paths connecting vehicle, ground, sun, and observer
Obscuration	From both sensor and sun (for shadows)
Nonaxisymmetric flowfield and radiation	Combine SPF1 correlations with 3-D flowfield studies. 3-D plume radiation model is applied to this flowfield
Airframe aerodynamic flow	Spatial variation in the adiabatic wall temperature
Interior thermal conductance	Account for transient temperature variation

HARDBODY module may be executed without executing the first five modules if no plume is desired in the scenario.

Target Sources Modeled in SPIRITS Code

configured to allow input through menus, as shorn in Fig.
19, and this feature will be enhanced in the PC version.
Since there are advantages, economic mostly, to using
government owned software, this avenue is under strong
consideration. If the SPIRITS code were modified for this
application, it would do the job of the first three planned
modules.

The work during phase one in this area has been done with
the AutoCAD software from Autodesk. This CAD software is
very versatile and can do the required tasks for this
module. However, the AutoCAD requires a trained operator
for sophisticated functions. If AutoCAD is the final
selection (also under consideration are packages such as
that by Intergraph. The basic functions required for this
module will be programmed (in LISP) for easy use by the
user. The advantage of using a software package such as
this is that the serious mechanical design user will have,
in addition to SCAD, the versatility of a sophisticated PC
CAD software package. If the SPIRITS approach is used, it
does not necessarily preclude the use of a CAD package.

4.2 Sources

The source issues are partially described by Fig. 20.
The source must be adequately defined to allow calculations
of radiant power levels expected to be generated. The
inputs which must be made to SCAD to account for the source
related factors concern the source/sensor geometry and the
source area, emissivity, and temperature. Several of the
geometry parameters will be provided by the previous module
if it has been invoked. The approach to this and other
modules is planned to be responsive to a variety of users.
For the most casual user a simple level of treatment will be
possible while for a user more interested in this phase of
the problem, more in depth treatments will be offered.

The simple treatment will be by a module which will
permit selecting a simple source shape, dividing that shape
into portions with individually selected temperatures and
emissivities. The module output will consist of the
spectrally resolved or the inband radiant power generated by
the source.

A prototype source module has been implemented using
the LOTUS spreadsheet. Fig. 21 shows the input section of
the spreadsheet and Fig. 22 shows the spectrally resolved
radiant intensity calculated from those inputs. The inputs
refer to a source which is subdivided into five portions.

```
┌──────────────────────────────┐
│ AVAILABLE TERRAINS MENU       │
├──────────────┐                │
│ MT/FOREST    │                │
├──────────────┴───────────────────────┐
│ COAST        AVAILABLE SCENES         │
│ URBAN         FILE NAME MENU          │
│ OCEAN                                 │
│ SKY          MT/FOREST 1 - BAND 1 ┌───────────────────────────┐
│              MT/FOREST 2 - BAND 1 │   HELP MENU               │
│ STOP             •              (SELECT FILE FOR SCENE        │
│                  •                 PARAMETERS)  ┌──────────────────────────────┐
│                  •              ├──────────────┤ MT/FOREST 1 - BAND 1         │
│                  •              │MT/FOREST 1 - BAND 1                          │
│              MT/FOREST 1 - BAND 2├─────────────┤ TERRAIN:      MT/FOREST       │
│              MT/FOREST 2 - BAND 2│MT/FOREST 2 - BAND 1                         │
│                  •                  •          │ CLOUDS ABOVE: NONE           │
│                  •                  •                                          │
│                  •                  •          │ CLOUDS BELOW: THIN HAZE      │
│                  •              MT/FOREST 1 - BAND 2                           │
│              ┌───────────────┐  MT/FOREST 2 - BAND 2 SEASON:   SPRING/         │
│              │ DISPLAY SCENE │      •                            SUMMER        │
│              │ PARAMETERS    │      •                                          │
│              └───────────────┘      •          │ TIME OF DAY:  3 p.m.         │
│              RETURN TO PREVIOUS RETURN TO PREVIOUS                             │
│                  MENU               MENU       │ BAND:         3-5 µm         │
│                                                                                │
│              STOP                              │ LOOK ANGLE:   100°ZENITH     │
│                                                               LOOK DOWN        │
│                                                                                │
│                                                │ ALTITUDE:     10,000 ft      │
│                                                                                │
│                                                │ COMMENT:      NONE           │
│                                                                                │
│                                                    ┌──────────────────────┐   │
│                                                    │ RETURN TO CONTINUE    │   │
│                                                    └──────────────────────┘   │
└──────────────────────────────────────────────────────────────────────────────┘
```

Examples of User Selection of Background Within SPIRITS

Fig. 19
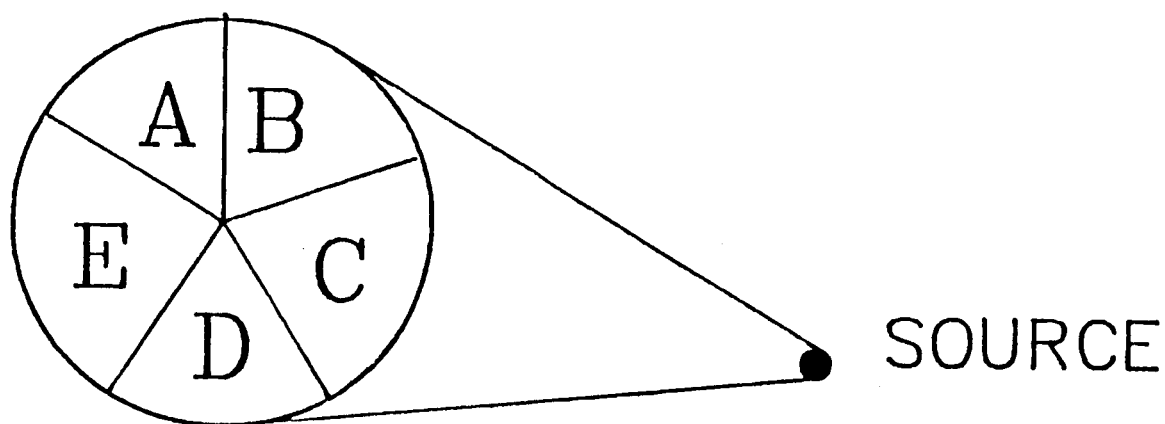
AREA

A% Ak Ae
B% Bk Be   D% Dk De
C% Ck Ce   E% Ek Ee

$$I = \int \sum L_\lambda (A^\circ \, k) \; dA d\lambda$$

FORTRAN, BASIC, LOTUS 123

Fig. 20

Page 57

	A	B	C	D	E	F	G	H
1	750	Temp (K)		1 Emisivty		0.2 Portion of area @ T1		
2	775	Temp (K)		1 Emisivty		0.2 Portion of area @ T2		
3	800	Temp (K)		1 Emisivty		0.2 Portion of area @ T3		
4	825	Temp (K)		1 Emisivty		0.2 Portion of area @ T4		
5	850	Temp (K)		1 Emisivty		0.2 Portion of area @ T5		
6								
7	0.1 First wavelength							
8	0.1 Wavelength Increment							
9	Last wavelength First+Increment*100=			10.1				
10								
11	1000 SQ M TOTAL AREA							
12								
13	Integral=0.477439			TOTAL RADIANT INTENSITY = 6427.090				
14	Integral=0.551732							
15	Integral=0.634096							
16	Integral=0.725070							
17	Integral=0.825206							
18								
19								
20								

3-Aug-87 04:41 PM

SPREAD SHEET EXAMPLE

Fig. 21

Planckian Radiation
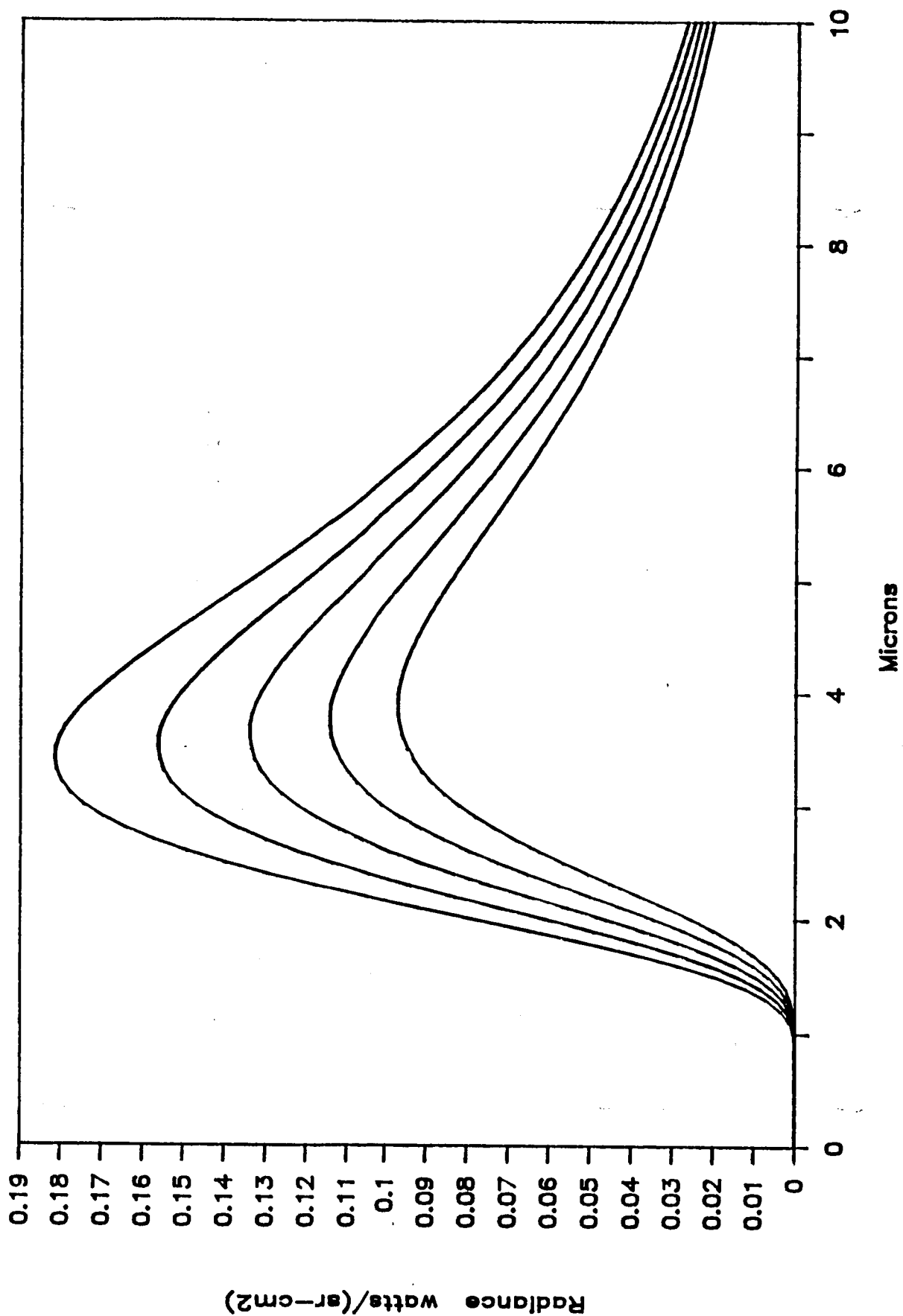
Radiance watts/(sr-cm2)

Microns

Fig. 22
Page 59

In this example, source is assumed to be a greybody with individual emissivities assigned to the different portions. The individual portions of the source have selectable temperatures, which are entered in kelvins. The calculations will be typically accomplished using wavenumbers for compatibility with atmospheric codes. Display of results will be optionally in wavenumbers or wavelengths.

The more in depth treatment will include a treatment of reflected sunlight, which can also take several forms. The simplest approach is to use a selected reflectance (a function of angle, etc.), the solar position and assume a 5900 blackbody viewed through the appropriate atmosphere. A more sophisticated approach to these scene generation issues is provided in other Aerodyne codes named SEGIR and AERIE. These codes treat the problem as depicted in Fig. 23.
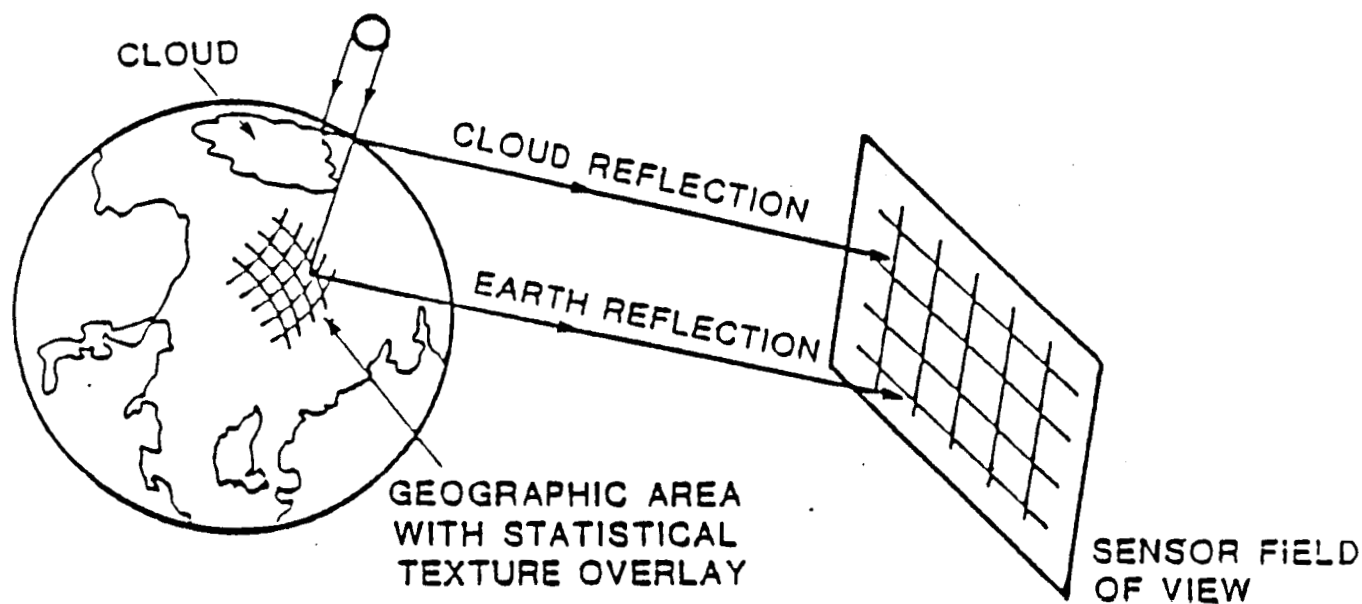
The first code (SEGIR) treats terrain using a segmented scene (derived for LANDSAT data) on which is superimposed a textured variation of both reflected and emitted light derived from ERIM data (Figs. 24 and 25). Strong solar scattering from water surfaces is included with allowance for wind driven surface roughness. Clouds are superimposed on the scene using physical cloud models and an analytical representation of the reflectivity obtained from scattering fro spherical particles.

The second code (AERIE) adds topographical features to model terrain, as described in Table 6, typically from DMA data, but with a statistical overlay of the critical underlying surface properties (reflectance, emittance, and thermal factors) to simulate the resulting texture in the scene. Reflectance and emittance from broken cloud decks are also included, as are effects of clouds and terrain shadows, and atmospheric transmittance and radiance.

4.3 Atmospheric Effects

Atmospheric effects will be treated with the LOWTRAN 6 software developed by the Air Force Geophysics Laboratory. Optionally the FASCODE software might be used as an extended option. The inputs to the LOWTRAN will be generally derived from the geometry/time module with the provision to input desired modifications. The climatic conditions will be entered when this module is invoked.

A FORTRAN version of LOWTRAN 5 was converted to the PC during this study with no significant problem, however, at least one vendor is marketing a version of LOWTRAN 6. It is

CLOUD

CLOUD REFLECTION

EARTH REFLECTION

GEOGRAPHIC AREA
WITH STATISTICAL
TEXTURE OVERLAY

SENSOR FiELD
OF VIEW
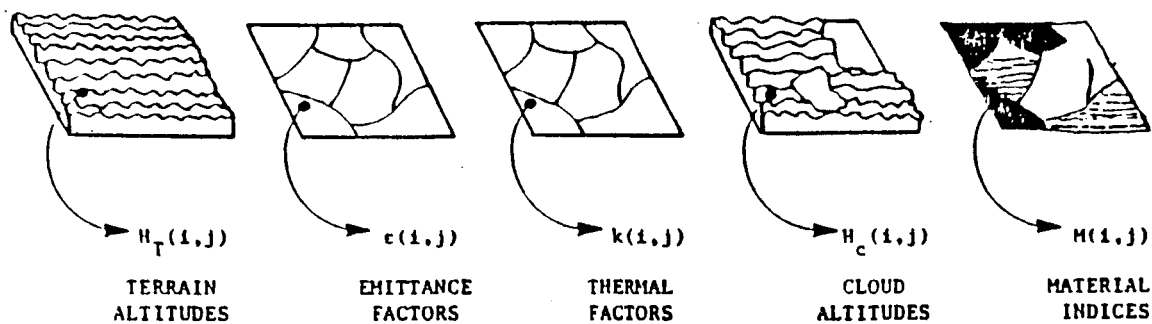
CLOUD REFLECTION COMPONENTS

ANALYTIC BIDIRECTIONAL SUN
SCATTERING MODEL

TWO WAY ATMOSPHERIC ATTENUATION
(LOWTRAN 6)

ATMOSPHERIC EMISSION (LOWTRAN 6)

SOLAR SCATTERING (LOWTRAN 6)

EARTH REFLECTION COMPONENTS

● AVERAGE COMPONENT DETERMINED BY GREY BODY
EMISSION (ASSUMED TEMP) AND SOLAR REFLECTANCE
USING EMISSIVITY AND REFLECTANCE OF TERRAIN TYPE

● ATMOSPHERIC EMISSION, SOLAR SCATTERING, AND
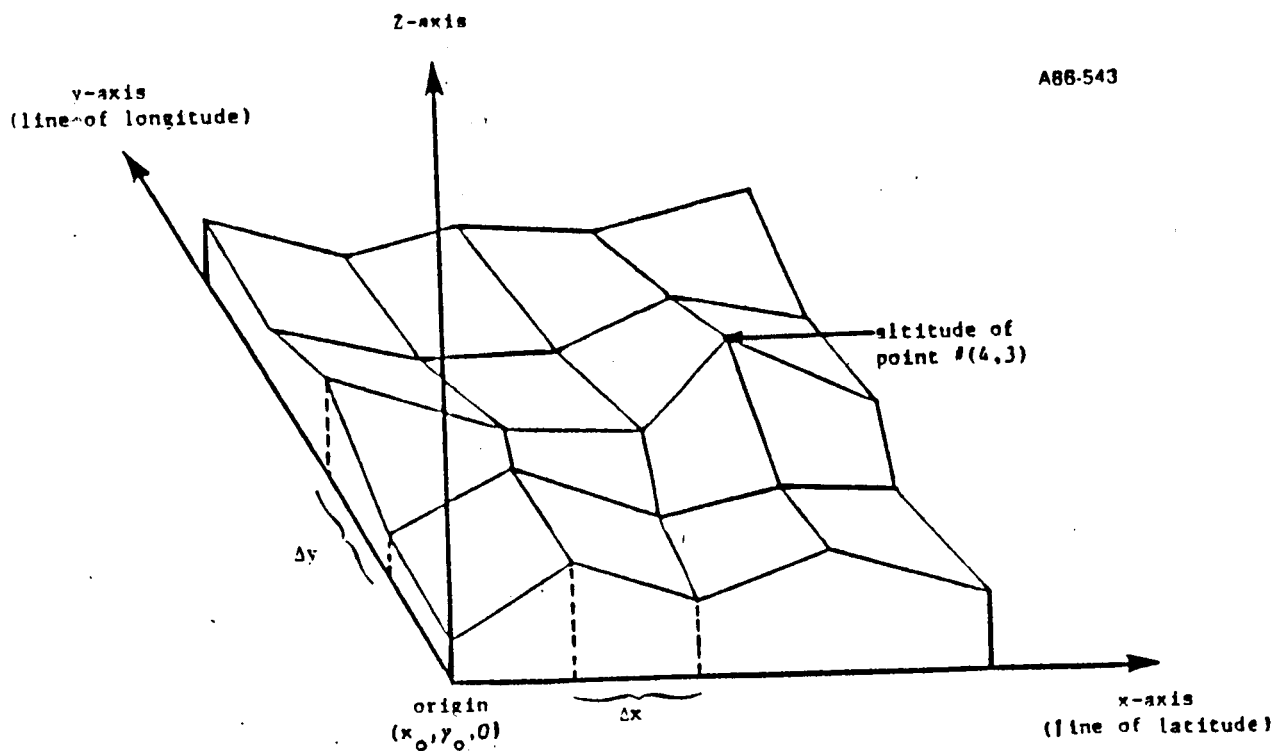ATMOSPHERIC ATTENUATION FROM LOWTRAN 6

BACKGROUND SCENE MODELING TECHNIQUE

Fig. 23

SCENE DESCRIPTION MATRICES

Fig. 24

SAMPLE FACET GRID

Fig. 25

Table 6

Component		Comments
Terrain:	Geometry	Faceted topography; varying materials
	Thermal Emission	Varying temperatures, emittances
	Solar Reflection	Varying reflectances; cloud shadows
	Emittance/Reflectance	Random with input spectral shape, correlation length, variance, and PSD shape for each material type
	Temperatures	Air temperature vs. altitude plus solar heating
	Thermal Constants	Random, with input correlation length, variance, and PSD shape for each material type
Cloud:	Geometry	Faceted topography
	Thermal Emission	Temperature varies with altitude
	Solar Reflection	Diffuse (water cloud) and specular (ice cloud)
Atmosphere:	Geometry	Paths between sun, ground/cloud, and sensor
	Radiation Transport	LOWTRAN6

SUMMARY OF AERIE CHARACTERISTICS

therefore not resolved whether the atmospheric codes used in SCAD will be from those supplied by the Bureau of Standards or the commercial packages supplied of ONTAR or by a SPIRITS or AERIE invoked LOWTRAN 6.

The LOWTRAN provides 20 cm-1 resolution over the .25 to 20 micron range (an example transmission curve derived from LOWTRAN 6 is shown in Fig. 26) and is deemed adequate for any foreseen sensor design problems. For the user who has a deeper interest in atmospheric effects, the FASCODE software may be optionally available. FASCODE does line calculations an offers much higher spectral resolution than LOWTRAN.

4.4   Collection Optics

The product of the geometry, source, and atmospheric effects is a resultant irradiance at the sensor collection optic. This module will be a very simple block which brings together the results determined by the previous modules. The most significant effort in this area will be the graphics development to innovatively display the product of the previous results.

The results from the section can permit sensitivity studies to be performed for different sources and atmospheric conditions. The disign of the optical train will take place in the folowing module, but will be designed to start with an entrance aperture determined in this step.

4.5   Optics

The greatest opportunity for innovation is in the area of the optical design module. Several commercial products designed for the PC have been evaluated and found to be almost useless to the typical engineer. The typical software presumes a great deal of knowledge of optics, is poorly documented, and under the best of circumstances, requires a lengthy training time for marginal proficiency. It is in this area that it is most tempting to develop a modern, effective optics design package.

Since most optical designs will be adaptations of a few basic designs, the approach planned is to offer the most common designs with provision for easy modifications. The optical package used will be invoked to permit either transparent use for the standard designs or access to the sophisticated optics package for the dedicated optical designer.
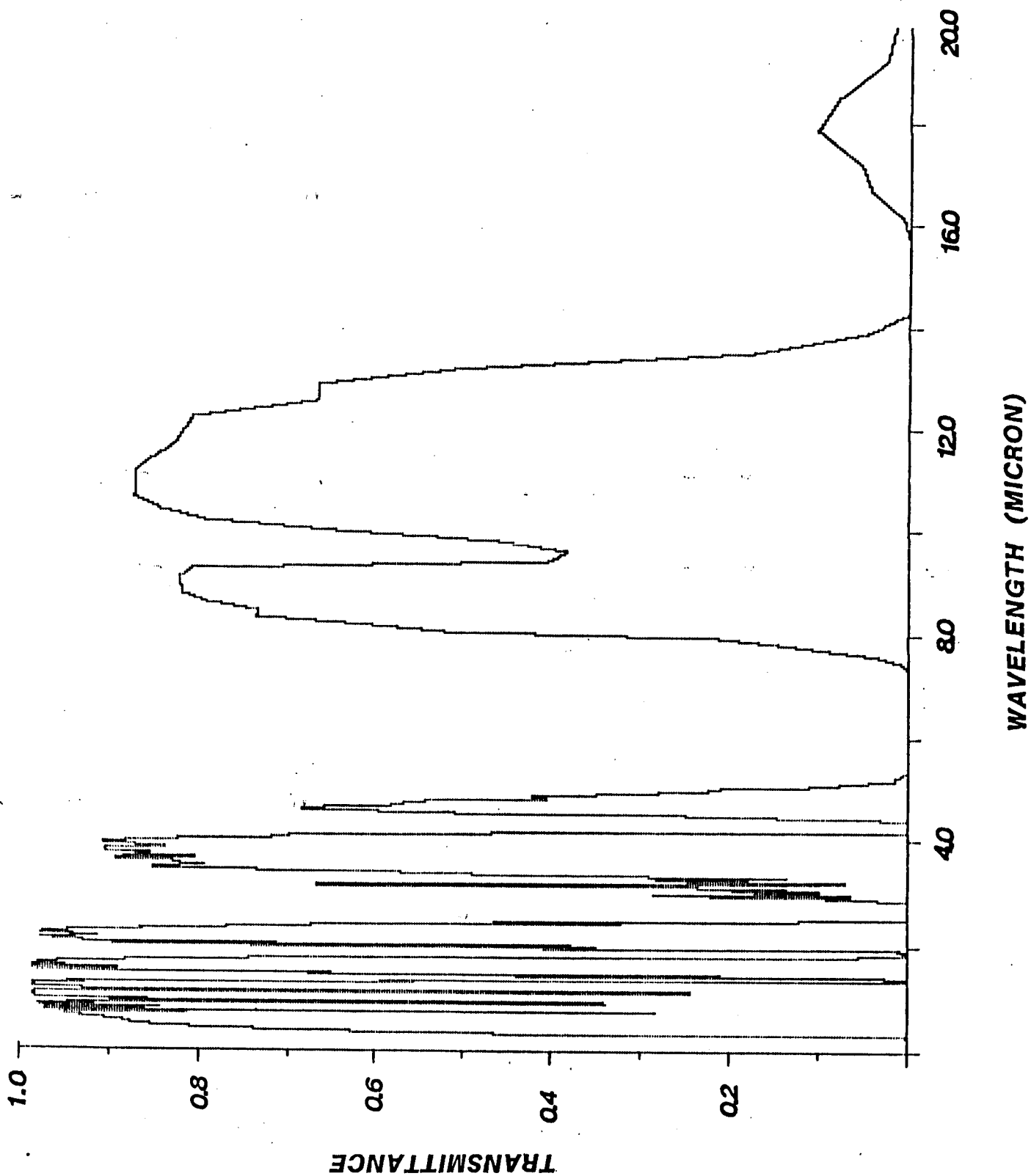
Fig. 26

An important aspect of the design of an optical system is the inclusion of the optical properties of the windows, lenses, mirrors, filters and the like which are included within the optical train.

The optics packages which have been reviewed for incorporation into SCAD have most of the features which are desirable for optics design except they are much too difficult to master. The Genesee Computer Center GENII-PC software appears to be typical of the optics packages currently available. It was designed in the 1970's for use on a large computer operating in batch mode and has been modified somewhat to operate on the IBM-PC. If this particular package is used, a substantial effort will be required to permit rational inputs, modifications and a reasonable output. There is some hope that the optics software manufacturers will improve their product during the near future and a more useful package will become available for SCAD.

4.6   Detector/Preamp

The detector/preamplifier is the transition stage between the optics and the electronics. From the optics standpoint the detector is the last stop in the system and may contain baffles, apertures, or the like which limit the potential field of view of the optical system. From the electronics point of view the detector is the first electronic element and has electrical characteristics which are of paramount importance to the performance of the system.

From the optics perspective issues of interest include the detector solid angle, the detector area and shape, the detector temperature, the detector time constant, the spectral detectivity, the detector linearity and the dynamic range of the detector. From the standpoint of the electronics the issues of interest include the impedance of the detector, the rms noise voltage, the time constant of the detector/preamplifier, and the like. The software treating the detector/preamplifier will be consequently be divided into two parts, one dealing with optics and one with the electronics.

The optics portion of this module will include the common detectors and their common configurations. The detector characteristics of common interest will be tabulated. The spectral dee-star and other figures of merit will be provided. The inputs to this module will include detector type, size, etc.

The spectral response of the detector will be convolved with the spectral irradiance on the detector to provide the output voltage expected from a given source.

The preamplifier portion of this module will include the common preamplifier configurations and their important figures of merit.

The desired output from the module is the detector/ preamplifier signal.

4.7   Electronics/Signal Conditioning

Following the detector preamplifier, the electronics and signal conditioning elements which may be included in a system are many and varied. In a simple non-scanning radiometric system the analog electronics may include amplifiers, integrators, summing amplifiers, high and low pass filters, isolation amplifiers, and others. In a scanning system the electronics are generally even more complicated.

As was the case in several of the preceding optics modules, the first level of this module will be aimed toward the preliminary design of the sensor system. The first level will include the basic building blocks which will be assembled in several typical configurations. The blocks will be easily modified and rearranged. The product of this level design will be a detailed block diagram of the desired electronic and signal conditioning system. The basic gain requirements, the noise figures, the response time, the expected signal level for a given source, and the like will be determined.

The software packages under consideration for this module include MicroSim Corp.'s PSpice and Visionics Corp.'s EE Designer.

4.8   Data Storage/Data Transmission

At this time, it is planned to treat the data storage and transmission areas in a cursory manner. The objective of the sensor developer does not generally include the design of the data storage and telemetry system. He does have to address the issues related to generating reasonable volumes of data and the like so some consideration will be made for these critical areas.

5.0   MERGING

The SCAD components have been identified or considered in preceding sections. The degree of utility with which these components may be applied depends upon several factors. Chief among these factors are their ease of use, their applicability, and their compatibility. The greatest effort in the design of SCAD is planned in the area of building the shell which provides interfaces between the various software components which will constitute SCAD.

During much of the phase one effort, several software packages have been scrutinized for applicability to the chore of serving as host to the various component packages previously discussed. Some of the software packages which may be used as components have also been considered as potential building blocks for the shell. The AutoCAD software has been strongly considered since it provides some of the graphics capabilities required and does possess some interfacing capabilities. The ability to work within MS-DOS and its ability to use customized menus makes it a viable candidate to provide the shell within which to build SCAD. Several other software packages, such as ASYST and WINDOWS, proved less suitable for this application although perhaps useful as tools for later expansions of SCAD.

For a time, the LOTUS 123 software was considered as a candidate software for developing the shell. For a portion of SCAD the LOTUS 123 software could be used to build individual components and to provide the integration of the components. For example, the output from the first four components in the SCAD as shown in Fig. 2 can be reduced to a matrix of numbers, such as that shown in Fig. 27. This n x m matrix contains much of the information required to define the sensor collection area, bandpass filter, and detector. The matrix is very amenable to being handled by a spreadsheet software such as LOTUS 123. The user skills required to use SCAD are anticipated to be those of an entry level 123 user, so there is impetus to use that software. The major deficiency with using 123 as a component is the difficulty with interfacing it to another program. It is very easy to import or create message files to and from 123, but at this time it appears to be difficult to have the interfacing be transparent to the user. Another reason it was attractive to consider using 123, was that it includes some plotting capabilities. On the other hand, a more sophisticated graphics package was desirable.

$$\begin{pmatrix}
\nu_1 = 500 & \lambda_1 = 20 & A' \; \epsilon'_1 \; L'_1 & \cdots & A^\circ \; \epsilon^\circ_1 \; L^\circ_1 & L_1 \; I_1 \; \tau'_1 \; \tau_1 \; I_1 & E_1 \; G_1 \; R_1 \; E_1 \\
\cdot & \cdot & \cdot & & \cdot & \cdot \; \cdot \; \cdot \; \cdot \; \cdot & \cdot \; \cdot \; \cdot \; \cdot \\
\cdot & \cdot & \cdot & & \cdot & \cdot \; \cdot \; \cdot \; \cdot \; \cdot & \cdot \; \cdot \; \cdot \; \cdot \\
\cdot & \cdot & \cdot & & \cdot & \cdot \; \cdot \; \cdot \; \cdot \; \cdot & \cdot \; \cdot \; \cdot \; \cdot \\
\nu_{2000} = 40500 & \lambda_{2000} = 0.25 & A' \; \epsilon'_{2000} L'_{2000} & \cdots & A^\circ \; \epsilon^\circ_{2000} L^\circ_{2000} & L_{2000} \; I_{2000} \; \tau^\tau_{2000} I_{2000} & E_{2000} \; G_{2000} \; R_{2000} \; E_{2000}
\end{pmatrix}$$

A^n = % of area & $\sum_n^5 A$ = 100%

G = Geometry factor from Optics
R = Normalized response of sensor

n = 1-5

LOWTRAN

$$\begin{pmatrix} \epsilon'_1 \\ \cdot \\ \cdot \\ \cdot \\ \cdot \\ \epsilon'_{2000} \end{pmatrix}$$

ϵ° = CONSTANT

OR

$$\begin{pmatrix} \nu_1 & & \tau_1 \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \cdot & & \cdot \\ \nu_{2000} & & \tau_{2000} \end{pmatrix}$$

MATRIX

Fig. 27

After considerable attention has been addressed to the investigation and evaluation of the previously mentioned PC based softwares for use in developing the SCAD shell, the conclusion is none of them would perform as well as desired for SCAD. At this time the choice appears to be to construct that shell software using a high level language, such as LISP, and an AI shell such as KES from Software A&E.

6.0 GRAPHICS

Excellent graphics is considered to be of paramount importance to the success of any future software which will be used by a general audience. Therefore, considerable attention is planned for the implementation of a easy to use but very graphic set of tools.

Each component will include a graphical representation of the inputs made to that module and will also graphically display the results of that module.

The graphics planned for the geometry component of SCAD will include a map of Earth with zoom capabilities for finding topographical features, geodesic location and political boundaries. The location of the sensor and target will be available in the form of easy to understand monitor pictures and drivers will be provided for output to a variety of hardcopy devices.

The graphics for the atmospheric transmission will include a visual presentation showing the relative position of sensor, sun, and source. The atmospheric conditions will be presented graphically and the atmospheric transmission will be displayed as a plot of transmission versus wavenumber or wavelength. The atmospheric emission will be displayed as radiance versus wavenumber or wavelength.

Since the function SCAD serves is to provide aid in the design of optical sensors, the greatest attention to graphics will be made in the area of optical design. In the vein of CAD, the system will offer output of the final design both with determinations of design parameters but also will permit the output of so called conceptual drawings as well as detailed mechanical drawings of the sensor system.

7.0   EXPANSION

The development of SCAD will provide two products which may be expanded to serve other and larger audiences.   First the SCAD can be expanded in several ways to enhance its performance.   It can also be expanded to include capabilities required by other sensor designers than those examining earth resources.   For example, the SCAD can easily be expanded to be more useful to DOD designers.   But, perhaps the most opportunity for expansion is in the area of applying the shell structure to other problems using other component softwares.   The SCAD shell will have addressed the problem of interfacing to older unwieldy softwares and the techniques should be in hand to expedite the handling of similar softwares.   Also, the shell will already have built in utilities, sucha s a broad graphics capability and device handlers.

The design of the SCAD will be with the aim of adding further capabilities as required for more sophisticated sensor design as well as application to similar problems. One of the first potential outgrowths of SCAD is its application by DOD users who are involved with SDI or space defense designers.

8.0   DISCUSSION

The work described has been directed toward establishing a detailed plan to assemble a set of software tools which can be used in the design of space based optical sensors.   The preliminary plan was to incorporate as much previously developed software as possible into an easy to use package.   That preliminary plan has been followed and appropriate softwares have been examined for applicability to this problem.   The most promising softwares and areas of potential difficulty have been identified.

9.0 BIBLIOGRAPHY

1. The Infrared Handbook, edited by W.L. Wolfe and G.J. Zissis, Office of Naval Research Department of the Navy, Arlington, Va., United States Government Printing Office, 1978.

2. Handbook of Military Infrared Technology, Editor William L. Wolfe, Naval Research Labratory, US Government Printing Office 1965.

3. Lecture Notes, Infrared Physics and Technology, A Short Course presented By UTSI, Course Director A.A. Mason Nov. 1979.

4. Optoelectronics Theory And Practice Edited by Alan Chappell, McGraw Hill Book Company, New York 1978.

5. Chemical Instrumentation: A Systematic Approach, Howard A. Strobel Addison-Wesley Publishing Co. Reading Mass 1973.

6. Handbook of Infrared Radiation from Combustion Gases, C.B. Ludwig, W. Malkmus, J.E. Reardon, J.A.L. Thomson, Editors- R. Gonlard, J.A.L. Thomson, NASA SP-3080.

7. Optics, E. Hecht and A. Zajac, Addison-Wesley Publishing Company, Reading, Massachusetts, 1979.

8. Concepts of Classical Optics, John Strong, W.H. Freeman Co., San Francisco, 1978.

9. Principles of Optics, Max Born and Emil Wolf, Fifth Edition, Pergamon Press, New York, 1975.

10. Modern Optical Engineering, Warren J. Smith, McGraw Hill Book Company, New York, 1966.

11. "Optics for the Electronics Engineer", Electro-Optical Systems Design, February 1977.

12. "The F-Stops Here", M.R. Hatch and D.E. Stoltzman, Optical Spectra, June 1980.

13. "Complete Analysis of a Two-mirror Unit Magnification System. Part 1, A. Suzuki, Applied Optics, Vol. 22, No. 24, December, 1983.

14. "Complete Analysis of a Two-mirror Unit Magnification System. Part 2, A. Suzuki, Applied Optics, Vol. 22, No. 24, December, 1983.

15. Infrared Detectors, edited by R.D. Hudson Jr. and J.W. Hudson, Dowden, Hutchinson and Ross Inc. Distributed by Halsted Press a division of John Wiley and Sons Inc., 1975.

16. "New Infrared Dectors", E.H. Putley Part 5, Advances in Geophysics ,Vol. 14, edited by H.E. Landsberg and J. Van Mieghem, Academic Press, New York, 1970.

17. "Cadmium-Telluride Detector Has Highest Sensitivity Yet", Electronic Design, Vol. 12, June 1974.

18. "HgCdTe:Number One in Night Vision" R. Martineau, G. Robillard and T. Wong, Optical Spectra, July 1979.

19. "Implementation of a System of Optical Calibration Based on Pyroelectric Radiometry", W.M. Doyle, B.C. McIntosh and Jon Geist, Optical Engineering, Vol. 15, No. 6, Nov./Dec. 1976.

20. "Cryogenic Semiconductor Bolometers", N.A. Pankratov and V.P. Korotkov, Optical Technology, Vol. 41, No. 4, February 1974.

21. "The General Theory of Bolometer Performance", R. Clark Jones, Journal of the Optical Society of America, Vol. 43, No. 1, January 1953.

22. "Application Note AN-10", C.B. Roundy, Spiricon, Logan, Utah.

23. Solid State Electronics, Shyh Wang, Mcgraw-Hill Book Company, New York, 1966.

24. "Pyroelectric Null Detector for Absolute Radiometry", Pradhan,M.M. and R.K. Garg, Applied Optics, Vol. 21, No. 24, Dec. 1982.

25. "Infrared Thermal Detectors:A Comparison", Chao Huang, Optical Spectra, September 1978.

26. "Pyroelectric Vidicons – The Ir Imaging Dark Horse", B. Singer, Electro-Optical Systems Design, July 1975.

27. "The Pyroelectric/CCD Focal Plane Hybrid: Analysis and Design for Direct Charge Injection", R. Watton, P. Manning, D. Burgess and J. Gooking, Infrared Physics, Vol. 22, 1982.

28. Solid State Electronics, Shyl Wang, McGraw Hill Book Company, New York, 1966.

29. "Principles of Electronic Instrumentation", A. James Diefenderfer, W. B. Saunders Co., Philadelphia, 1972.

LIST OF SYMBOLS

A	Area (cm) or Electric Field Magnitude
B	Magnetic Field
c	Specific Heat or Speed of Light
C	Conductivity
d	Distance
D	Detectivity
D*	Dee-star, Normalized Detectivity
e	Excited Electron Lifetime
E	Irradiance
f	Focal Length (cm) or Frequency (Hz)
f/	F-number
F(T)	Pyroelectric Coefficient
h	Planck's Constant or Detector Thickness
i	Current (amperes)
I	Radiant Intensity (watt/sr)
k	Boltzman's Constant
K	Thermal Conductance
l	Length (cm)
L	Radiance
m	Modulation Index
M	Emittance
n	Index of Refraction
N	Noise
NEP	Noise Equivalent Power
NF	Noise Figure
Q	Power
QE	Quantum Efficiency
r	Reflection Coefficient
R	Responsivity
s	Distance
S	Signal Voltage
t	Time or Transmission Coefficient
T	Temperature (Kelvins)
u	Electron Mobility
V	Frequency (Hz)
$\propto$	Absorptivity (%)
ϵ	Emissivity (%)
θ	Angle (degree)
	Wavelength (microns)
μ	Permeability Constant
$\emptyset$	Phase Difference
Γ	Reflectivity (%)
σ	Wavenumber (cm) or Stefan-Boltzman's Constant
τ	Transmissivity (%) or Time Constant (second)
w	Angular Frequency (radians/second)
Ω	Solid Angle (sr)
δ	Delta