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IRRADIANCE FROM STARS BASED ON BLACKBODY THEORY

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16. ABSTRACT

A Fortran computer program is presented that calculates the stellar spectra given the star temperature and visual magnitude. The program uses blackbody theory and was developed to aid in analysis of the Space Telescope Fine Guidance Sensor.

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TECHNICAL MEMORANDUM

IRRADIANCE FROM STARS BASED ON BLACKBODY THEORY

INTRODUCTION

This report describes a computer program which calculates a theoretical blackbody curve for a star when given only the star's temperature and visual magnitude. The program was written to produce approximate stellar spectra to be used in the design of the Space Telescope Fine Guidance System (FGS). In addition to the blackbody curve, the program calculates the number of photons that would be received from the star by the Space Telescope per 25 msec interval in wavelength increments of 0.2 microns. The equations used for the computation work best for stars that emit primarily in the range from near infrared to ultraviolet. Cooler stars may not give accurate results.

DESCRIPTION OF PROGRAM CALCULATIONS

This computer program is designed to give data for a blackbody curve and a count of photons emitted by the star. The only inputs are the temperature and visual magnitude of the star being used.

The first step in the program is to find the visible irradiance for a star $[I(m_v)]$ using equation (1).

$$m_v = -2.5 \log_{10} [I(m_v)/I_o] \qquad (1)^1$$

Where

I_o = irradiance of zero magnitude star

m_v = visible magnitude

Equation (1) easily converts to equation (2) with $I(m_v)$ dependent on I_o and m_v.

$$I(m_v) = I_o \times 10^{-(0.4 m_v)} \text{ Watts cm}^{-2} \qquad (2)$$

To find the blackbody visible response fraction $[\eta_e(T)]$ equation (3) is used.

$$\eta_e(T) = \frac{\int W_\lambda(T)\, Se_\lambda \, d\lambda}{\int W_\lambda (T)\, d\lambda} \qquad (3)^1$$

Where

Se = the human eye response[2]

$W_\lambda(T)$ = the Planck function, equation (4)

T = temperature in degrees Kelvin

λ = wavelength

and the Planck function wavelength (λ) is given by,

$$W_\lambda(T) = \frac{2\pi\ c^2\ h}{\lambda^5\ (e^{hc/\lambda kt}-1)}\ \text{Watts/cm}^2/\mu \qquad (4)^3$$

where

c = speed of light

κ = Planck's constant

h = Boltzman's constant

The top integral in equation (3) is calculated in the program over lengths of 0.34 to 0.82 with a $d\lambda$ (delta wavelength) of 0.02 microns. The bottom integral is the Stefan Boltzman function which is equal to

$$5.679 \times 10^{-12} \times T^4 \text{ watts cm}^2 \qquad (5)^1$$

To find the maximum value of the Planck function [$W_\lambda max(T)$] equation (6) is used.

$$W_\lambda max(T) = 1.25 \times 10^{-15} \times T^5 \text{ watts/cm}^2/\mu \qquad (6)^1$$

Using equations (2), (3), (5) and (6), the peak of the blackbody curve becomes equation (7).

$$H_\lambda peak = \frac{I(m_v)}{\eta_e(T)} \times \frac{W_\lambda Max(T)}{\int W_\lambda(T)\, d\lambda} \text{ watts/cm}^2/\mu \qquad (7)^1$$

From the value for $H_\lambda$peak and using equation (8),

$$H(\lambda,T) = \frac{0.2900}{(\lambda T)^5\,(e^{1.438/\lambda T}-1)} \times H_\lambda \text{peak watts/cm}^2/\mu \qquad (8)^1$$

values for the blackbody curve are calculated for each (wavelength) used. This data then can be used to create a plot for the blackbody star.

To find the amount of watts/μ received, the blackbody data was multiplied by a collecting aperture (A). The aperture used in the sample is from the Space Telescope. To give an approximation in watts over an area around the wavelength increments the watts/μ is multiplied by 0.02 microns.

$$H_{st}(\lambda,T) = H(\lambda,T) \times A \times 0.02 \text{ watts} \qquad (9)$$

Watts are divided by hc/λ to give photons. As is shown in equation (10).

$$Hp(\lambda,T) = \frac{H_{st}(\lambda,T)}{hc/\lambda} \text{ photons/sec} \qquad (10)$$

CONCLUSION

By the use of this computer program, theoretical values are created for a blackbody curve. These values are calculated from a star's visual magnitude and may be used to produce photon counts at certain wavelengths for use in many applications. These applications include throughput analysis of lenses and mirrors where efficiency is important.

The blackbody curve created with this program is only applicable outside the atmosphere. For operation inside the atmosphere, values of spectral absorption should be applied. The values calculated are assumed to be from a star which behaves as a "Planckian Emitter." There is evidence that while many stars behave this way, some do not. This is especially true for cooler stars.

CONSTANTS

*$I_o = 3.1 \times 10^{-13}$ watts cm^2

$c = 2.99793 \times 10^{10}$ cm/sec

$h = 6.626176 \times 10^{-34}$ J.S

$k = 1.380662 \times 10^{-23}$ J/K°

$\pi = 3.1415926$

$A = 3.89 \times 10^4$ cm^2 for Space Telescope

*Allen's Astrophysical Journal states that $I_o = 3.6 \times 10^{-13}$ watts cm^2, but to be conservative the Applied Optics value of 3.1×10^{-13} watts cm^2 is used.

EXAMPLE RUN OF PROGRAM

This program is currently being used in a throughput analysis program for the Fine Guidance System of the Space Telescope. The values for $H(\lambda,T)$ are normalized (Fig. 1) and multiplied with the throughput value of the other surfaces (Fig. 2), producing a sample of the amount of photons that will reach the optical detectors that produce a signal for fine pointing of the Space Telescope. Two example runs of the program show the number of photons emitted by the star.

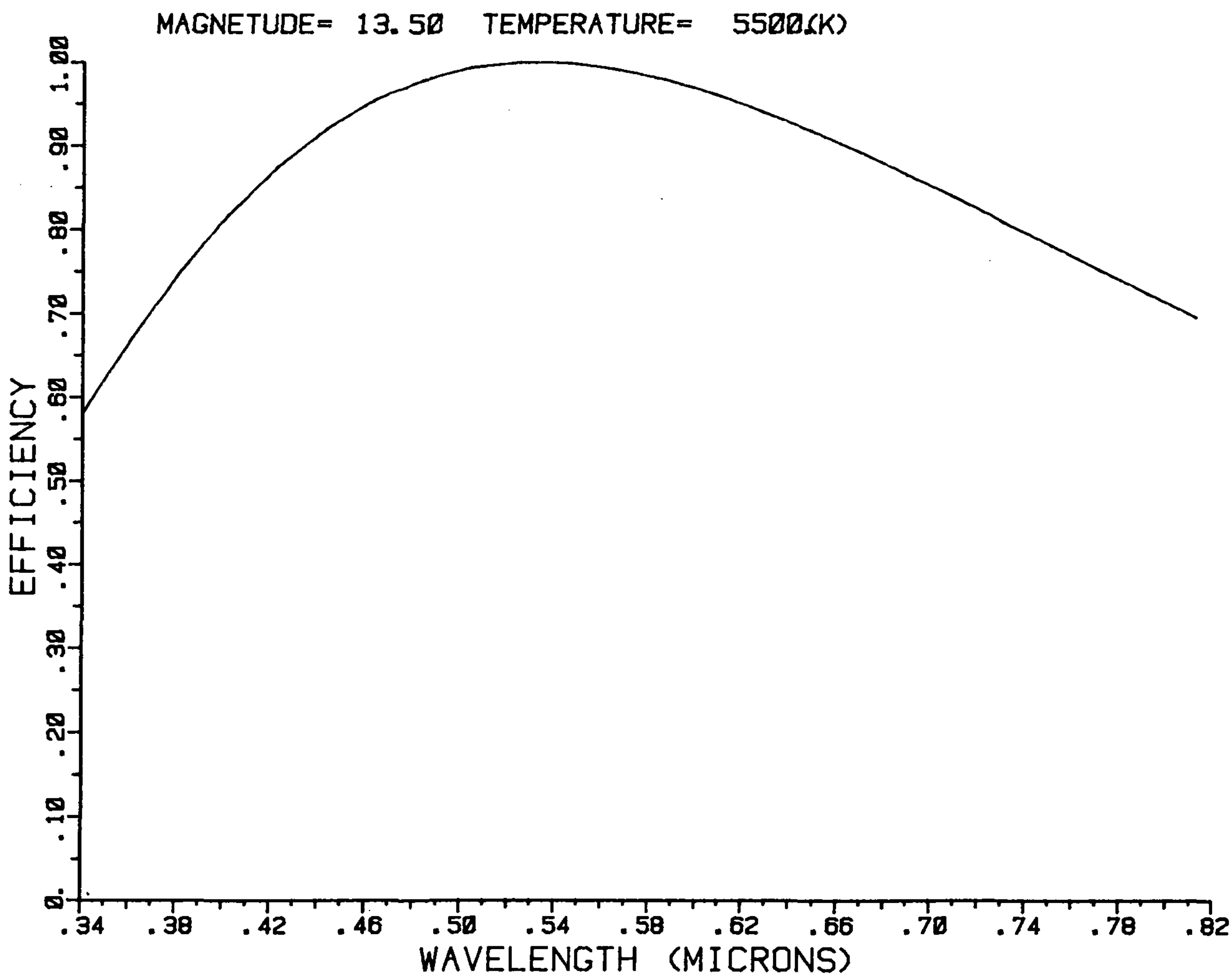

Figure 1. Normalized blackbody curve of a star.

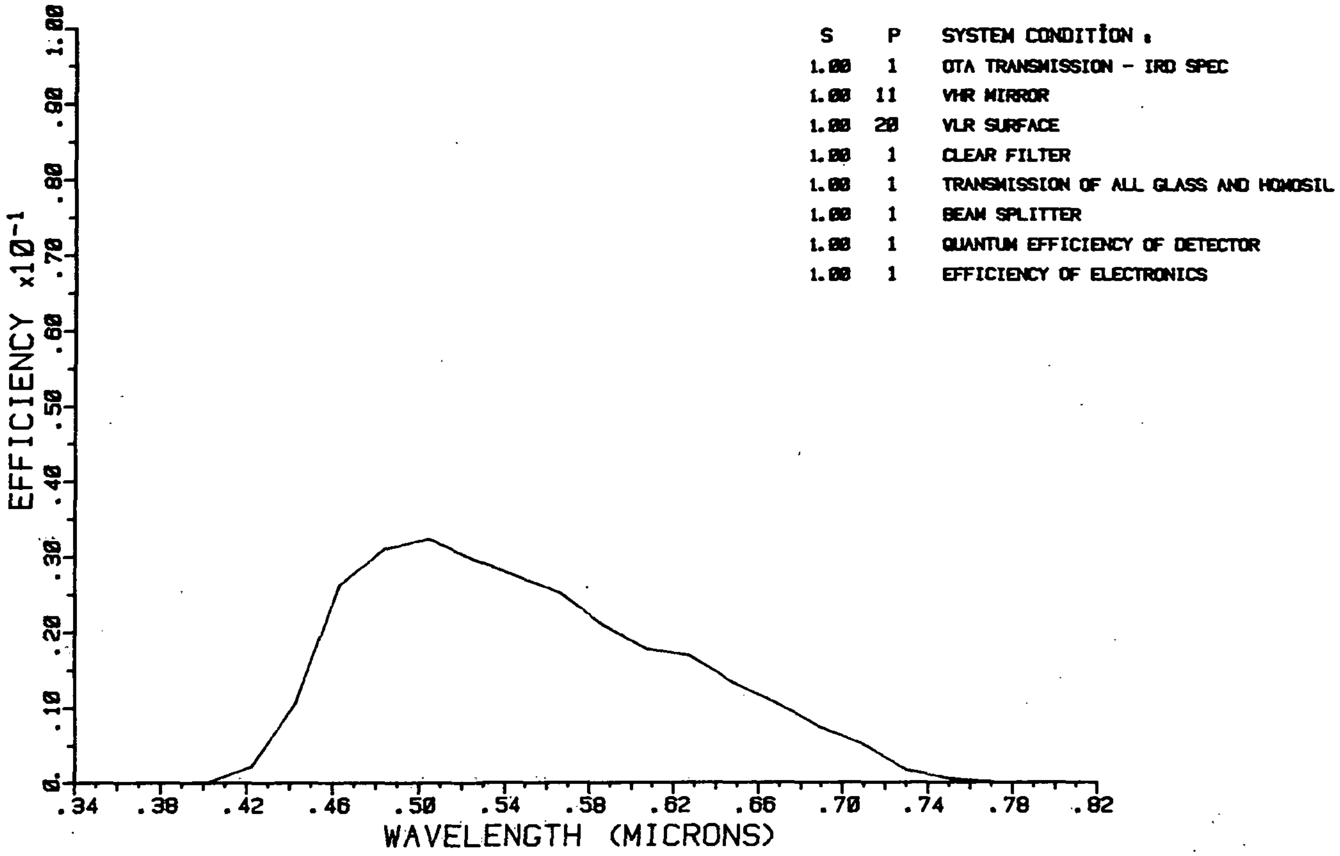

Figure 2. OTA-FGS throughput curve.

SAMPLE RUN OF PROGRAM BBDATAPROG

CONTROL COMMANDS

```
!SET F:20/EYERESP

!SET F:TT ME;DRC;BIN
```

START OF PROGRAM

```
!START BBDATAPROG


IN THIS BLACKBODY DATA PROGRAM, YOU WILL
ENTER A MAGNETUDE AND TEMPERATURE(K)
AND THE PROGRAM WILL COMPUTE THE PHOTONS PER
WAVELENGTH.

ENTER THE MAGNETUDE AND TEMPERATURE(K).
?13.5,5500
```

```
WAVELENGTH=   .340   H(LAMBDA)= .685511E-17   PHOTONS=    228.
WAVELENGTH=   .360   H(LAMBDA)= .789838E-17   PHOTONS=    278.
WAVELENGTH=   .380   H(LAMBDA)= .883652E-17   PHOTONS=    329.
WAVELENGTH=   .400   H(LAMBDA)= .964913E-17   PHOTONS=    378.
WAVELENGTH=   .420   H(LAMBDA)= .103264E-16   PHOTONS=    425.
WAVELENGTH=   .440   H(LAMBDA)= .108668E-16   PHOTONS=    468.
WAVELENGTH=   .460   H(LAMBDA)= .112750E-16   PHOTONS=    508.
WAVELENGTH=   .480   H(LAMBDA)= .115597E-16   PHOTONS=    543.
WAVELENGTH=   .500   H(LAMBDA)= .117323E-16   PHOTONS=    574.
WAVELENGTH=   .520   H(LAMBDA)= .118055E-16   PHOTONS=    601.
WAVELENGTH=   .540   H(LAMBDA)= .117921E-16   PHOTONS=    623.
WAVELENGTH=   .560   H(LAMBDA)= .117050E-16   PHOTONS=    642.
WAVELENGTH=   .580   H(LAMBDA)= .115561E-16   PHOTONS=    656.
WAVELENGTH=   .600   H(LAMBDA)= .113563E-16   PHOTONS=    667.
WAVELENGTH=   .620   H(LAMBDA)= .111156E-16   PHOTONS=    675.
WAVELENGTH=   .640   H(LAMBDA)= .108428E-16   PHOTONS=    679.
WAVELENGTH=   .660   H(LAMBDA)= .105454E-16   PHOTONS=    681.
WAVELENGTH=   .680   H(LAMBDA)= .102302E-16   PHOTONS=    681.
WAVELENGTH=   .700   H(LAMBDA)= .990262E-17   PHOTONS=    679.
WAVELENGTH=   .720   H(LAMBDA)= .956753E-17   PHOTONS=    674.
WAVELENGTH=   .740   H(LAMBDA)= .922884E-17   PHOTONS=    669.
WAVELENGTH=   .760   H(LAMBDA)= .888981E-17   PHOTONS=    662.
WAVELENGTH=   .780   H(LAMBDA)= .855313E-17   PHOTONS=    653.
WAVELENGTH=   .800   H(LAMBDA)= .822094E-17   PHOTONS=    644.
WAVELENGTH=   .820   H(LAMBDA)= .789495E-17   PHOTONS=    634.
*STOP* END OF PROGRAM
```

SAMPLE RUN OF PROGRAM BBDATAPROG

Run #2

CONTROL COMMANDS

```
!SET F:20/EYERESP

!SET F:TT ME;DRC;BIN
```

START OF PROGRAM

```
!START BBDATAPROG


IN THIS BLACKBODY DATA PROGRAM, YOU WILL
ENTER A MAGNETUDE AND TEMPERATURE(K)
AND THE PROGRAM WILL COMPUTE THE PHOTONS PER
WAVELENGTH.

ENTER THE MAGNETUDE AND TEMPERATURE(K).
?14.5,5500
```

```
WAVELENGTH=    .340    H(LAMBDA)= .272908E-17    PHOTONS=     91.

WAVELENGTH=    .360    H(LAMBDA)= .314441E-17    PHOTONS=    111.

WAVELENGTH=    .380    H(LAMBDA)= .351789E-17    PHOTONS=    131.

WAVELENGTH=    .400    H(LAMBDA)= .384140E-17    PHOTONS=    150.

WAVELENGTH=    .420    H(LAMBDA)= .411103E-17    PHOTONS=    169.

WAVELENGTH=    .440    H(LAMBDA)= .432617E-17    PHOTONS=    186.

WAVELENGTH=    .460    H(LAMBDA)= .448867E-17    PHOTONS=    202.

WAVELENGTH=    .480    H(LAMBDA)= .460201E-17    PHOTONS=    216.

WAVELENGTH=    .500    H(LAMBDA)= .467073E-17    PHOTONS=    229.

WAVELENGTH=    .520    H(LAMBDA)= .469986E-17    PHOTONS=    239.

WAVELENGTH=    .540    H(LAMBDA)= .469455E-17    PHOTONS=    248.

WAVELENGTH=    .560    H(LAMBDA)= .465987E-17    PHOTONS=    256.

WAVELENGTH=    .580    H(LAMBDA)= .460057E-17    PHOTONS=    261.

WAVELENGTH=    .600    H(LAMBDA)= .452105E-17    PHOTONS=    266.

WAVELENGTH=    .620    H(LAMBDA)= .442523E-17    PHOTONS=    269.

WAVELENGTH=    .640    H(LAMBDA)= .431660E-17    PHOTONS=    270.

WAVELENGTH=    .660    H(LAMBDA)= .419823E-17    PHOTONS=    271.

WAVELENGTH=    .680    H(LAMBDA)= .407272E-17    PHOTONS=    271.

WAVELENGTH=    .700    H(LAMBDA)= .394232E-17    PHOTONS=    270.

WAVELENGTH=    .720    H(LAMBDA)= .380892E-17    PHOTONS=    269.

WAVELENGTH=    .740    H(LAMBDA)= .367408E-17    PHOTONS=    266.

WAVELENGTH=    .760    H(LAMBDA)= .353911E-17    PHOTONS=    263.

WAVELENGTH=    .780    H(LAMBDA)= .340507E-17    PHOTONS=    260.

WAVELENGTH=    .800    H(LAMBDA)= .327283E-17    PHOTONS=    256.

WAVELENGTH=    .820    H(LAMBDA)= .314305E-17    PHOTONS=    252.
*STOP* END OF PROGRAM
```

```
*TY1-42
C      ********** BLACKBODY DATA PROGRAM **********
C
C
C      THIS PROGRAM IS DESIGNED TO CREATE DATA FOR
C      A BLACK BODY CURVE FROM A GIVEN TEMPERATURE
C      AND A GIVEN MAGNETUDE
C      WRITTEN BY WILLIAM JACOBS
C
       DIMENSION S(100),W(100),R(100),PHOTON(100)
       DIMENSION HST(100),H(100)
    10 WRITE(102,20)
    20 FORMAT('IN THIS BLACKBODY DATA PROGRAM, YOU WILL',/,
      $'ENTER A MAGNETUDE AND TEMPERATURE(K)',/,
      $'AND THE PROGRAM WILL COMPUTE THE PHOTONS PER',/,
      $'WAVELENGTH. ',/,
      $//,'ENTER THE MAGNETUDE AND TEMPERATURE(K).')
       READ(101,30)SMAG,TEMP
    30 FORMAT(2G)
C
C      CALCULATE VALUE FOR VISIBLE IRRADIANCE
C
       WPC=3.1E-13*(10**(-.4*SMAG))
       N=0
       VISUAL=0
       DO 50 N=1,24
C
C      INPUT VALUES OF EYERESPONCE FOR EACH WAVELENGTH
C
       READ(20,40)S(N)
    40 FORMAT(1G)
    50 CONTINUE
       N=0
       DO 60 WAVLEN=.34,.82,.02
       N=N+1
C
C      CONVERT MICRONS TO CENTIMETERS
C
       SD=WAVLEN*1E-4
C
C      CALCULATION OF PLANCK FUNCTION
C
       W(N)=3.74185E-12/((SD**5)*(EXP(1.4388/(SD*TEMP))-1))
*
```

```
*TY43-84
C
C     INTEGRATE EYE RESPONCE DATA TIMES PLANCK FUNCTION
C
      VISUAL=VISUAL+W(N)*S(N)*2E-6
   60 CONTINUE
      TOT=5.679E-12*TEMP**4
C
C     VALUE FOR VISIBLE RESPONCE FRACTION
C
      EFF=VISUAL/TOT
      N=0
      DO 80 WAVLEN=.34,.82,.02
      N=N+1
C
C     LOCATE PEAK OF BLACKBODY CURVE
C
      HPEAK=(WPC/EFF)*((1.29E-15*TEMP**5)/(5.679E-12*TEMP**4))
      SA=EXP(1.4380/((WAVLEN*1E-4)*TEMP))-1
C
C     CALCULATE VALUES FOR BLACKBODY CURVE
C     AT EACH WAVELENGTH INCREMENT
C
      H(N)=(.2900/((((WAVLEN*1E-4)*TEMP)**5)*SA))*HPEAK
C
C     AREA FOR SPACE TELESCOPE EQUALS 3.89E4 CM**2
C
      HST(N)=H(N)*3.89E4*.02
C
C     CALCULATE NUMBER OF PHOTONS FOR EACH WAVLENGTH
C
      PHOTON(N)=HST(N)/(1.9864776E-23/(WAVLEN*1E-4))
C
C     CONVERT PHOTONS/SEC TO PHOTONS/25MILLISEC
C
      PHOTON(N)=PHOTON(N)*.025
C
      WRITE(102,70)WAVLEN,H(N),PHOTON(N)
   70 FORMAT(/,1X,'WAVELENGTH= ',F6.3,3X,'H(LAMBDA)= ',1G,
     $3X,'PHOTONS=    ,F6.0)
   80 CONTINUE
      STOP'END OF PROGRAM'
      END
*
```

Variables in Program and Their Meaning

SMAG	Visual magnitude
Temp	Temperature of star
WPC	Visible irradiance
S(N)	EYE response data
W(N)	Planck function
Visual	Integration value of visible spectrum
TOT	Stefan Boltzman function
EFF	Blackbody visible response fraction
HPEAK	Peak of blackbody curve
H(N)	Values for blackbody curve
Hst(N)	Values represented in watts
Photon (N)	Number of photons at each wavelength

LIST OF EYE RESPONSE DATA FOR PROGRAM

```
!E EYERESP
EDIT HERE
*TY


     .340 0.0
     .360 0.0
     .380 0.00004
     .400 0.0004
     .420 0.0040
     .440 0.023
     .460 0.060
     .480 0.139
     .500 0.323
     .520 0.710
     .540 0.954
     .560 0.995
     .580 0.870
     .600 0.631
     .620 0.381
     .640 0.175
     .660 0.061
     .680 0.017
     .700 0.0041
     .720 0.0
     .740 0.0
     .760 0.0
     .780 0.0
     .800 0.0
     .820 0.0
*
```

REFERENCES

1. Ramsey, R. C.: Spectral Irradiance from Stars and Planets Above the Atmosphere, from 0.1 to 100.0 microns. Applied Optics, Vol. 1, No. 4, July 1962, pp. 465-471..

2. RCA Electro-Optics Handbook Technical Series EOH-11, page 54.

3. RCA Electro-Optics Handbook Technical Series EOH-11, page 35.

APPROVAL

IRRADIANCE FROM STARS BASED ON BLACKBODY THEORY

By William A. Jacobs

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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Director, Information and Electronic
Systems Laboratory

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