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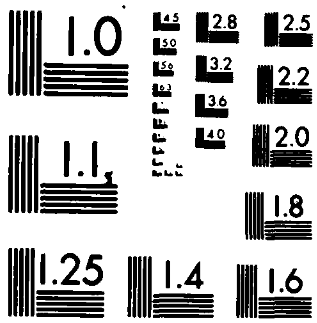

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SUBFLR—AN ALGORITHM FOR CALCULATING SURFACE-BASED FLIR DETECTION RANGES

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25 January 1983

Interim Report: January—September 1982

Prepared for
Naval Sea Systems Command

Superseded
AD-A126981
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ADMINISTRATIVE INFORMATION

This work was conducted over the period January–September 1982 and supported by the Electromagnetics and Acoustics Division of the Naval Sea Systems Command under Program Element 62759N, Project Number F59551.

Released by
JH Richter, Head
Ocean and Atmospheric
Sciences Division

Under authority of
JD Hightower, Head
Environmental Sciences Department

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NOSC Technical Document 568 (TD 568)	2. GOVT ACCESSION NO. AD. A129730	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SUBFLR - AN ALGORITHM FOR CALCULATING SURFACE-BASED FLIR DETECTION RANGES		5. TYPE OF REPORT & PERIOD COVERED Interim January–September 1982 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) HG Hughes MR Paulson FP Snyder		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Ocean Systems Center San Diego, CA 92152		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 62759N, F59551
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Sea Systems Command Washington, DC 20362		12. REPORT DATE 25 January 1983 13. NUMBER OF PAGES 22
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Infrared detection
Aerosol extinction model
Extinction coefficients
Aerosol distribution
Absorption coefficients

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A model is described for assessing the effects of scattering and absorption of infrared radiation by atmospheric aerosols and gases on the ranges at which surface targets can be detected against their natural backgrounds by a surface-based FLIR system. The equations from the model are implemented via a computer program which calculates detection range.

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S N 0102-LF-014-6601

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I. INTRODUCTION

This report describes a model for assessing the effects of scattering and absorption of infrared radiation by atmospheric aerosols and gases on the ranges at which surface targets can be detected against their natural backgrounds by a surface-based FLIR system. In particular, equations are fitted to curves of the 8-12 μm band averaged molecular (range dependent) absorption and aerosol extinction coefficients calculated using LOWTRAN 5[1] and the Navy aerosol model[2] (to appear in LOWTRAN 6), respectively, for differing meteorological conditions. These equations are implemented via a Hewlett-Packard model 9845 computer program (listed in Appendix form) which calculates the detection ranges of targets, using as inputs the FLIR system parameters and measurable meteorological parameters.

II. DETECTION MODEL

The FLIR system minimum detectable temperature difference at a spatial frequency ν, MDT(ν), is that temperature difference between a square target of angular subtense $(2\nu)^{-1}$ and a uniform background which

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1. F.X. Kneizys, E.P. Shettle, W.O. Gallery, J.H. Chetwynd, Jr., L.W. Abreu, J.E.A. Selby, R.W. Fenn and R.A. McClatchey, "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 5," AFGL-TR-80-0067, 21 February 1980.

2. Private communications, Stuart G. Gathman, Code 4320, Naval Research Laboratory.

corresponds to a 50% probability of detection for the average observer. It defines the system's ability to discern an object which may be too small to spatially resolve but is hot enough to exceed the detection threshold for one detector.

MDT(ν) can be calculated from an expression given by Nash and Wood[3] as

$$MDT(\nu) = 4\nu(SNRT)(NET)\left[1 + (2\nu r_s)^2\right]^{1/2}\left(\frac{\Delta x \Delta y}{\pi t_e F_r}\right)^{1/2} \qquad (1)$$

where

SNRT = perceived signal-to-noise threshold for detection, (usually set to 2.5)

NET = noise equivalent temperature (°C)

r_s = system resolution (mrad)

Δx = detector in-scan angular subtense (mrad)

Δy = detector cross-scan angular subtense (mrad)

t_e = eye integration time (usually set to 0.1 sec)

F_r = Frame rate (frames/sec)

Equation (1) is applicable to common-module FLIR systems and when the system's modulation transfer function is due only to the detector and optics.

3. C. Nash and J.T. Wood, "Calculation of MRT and MDT for Thermal Imaging Sensors," DCS Corporation Report to NSWC under Contract No. N60921-81-M-4917, 24 August 1981.

Real targets are generally complex in shape. Here, for modeling purposes, the target's composite areas are summed to give an equivalent rectangular area of width W_t and height H_t. The target solid angle subtense is found by dividing its area by its range squared (R^2), and the angular subtense θ is the square root of this. The target spatial frequency is then given by $\nu = (2\theta)^{-1}$. Equation (1) can now be written

$$MDT(\nu) = C_1 \; \nu \left(1 + C_2\nu^2\right)^{1/2} \tag{2a}$$

$$MDT(R) = C_1 \frac{R}{2(H_t W_t)^{1/2}} \left[1 + C_2 \; \frac{R^2}{4H_t W_t}\right]^{1/2} \tag{2b}$$

where C_1 and C_2 are system constants given by

$$C_1 = 17.84(NET) \left(\frac{\Delta x \Delta y}{F_r}\right)^{1/2} \tag{3a}$$

$$C_2 = 4r_s^2 \tag{3b}$$

The perceived temperature difference, $\Delta T_p(R)$, between a target at range R and its background is the actual temperature difference ΔT_a degraded by the atmospheric transmittance, $\langle\tau(R)\rangle$, band-averaged over the response of the the system, ie,

$$\Delta T_p(R) = \Delta T_a \langle T(R)\rangle \tag{4}$$

The band-averaged transmittance is defined as

$$\langle\tau(R)\rangle = e^{-\langle\beta(R)\rangle R} \tag{5}$$

where

$$\langle\beta\rangle = \langle\beta_a\rangle + \langle A_m(R)\rangle \tag{6}$$

and $\langle\beta_a\rangle$ and $\langle A_m(R)\rangle$ are the band-averaged aerosol extinction and range-dependent molecular absorption coefficients which will be derived in the following sections.

The detection range is then defined as that range where $\Delta T_p(R) \equiv MDT(R)$ or

$$\Delta T_a e^{-\langle\beta(R)\rangle R} = C_1 \frac{R}{2(H_t W_t)^{1/2}} \left[1 + \frac{C_2 R^2}{4H_t W_t}\right]^{1/2} \tag{7}$$

Given the atmospheric parameters, target dimensions and actual temperature difference, the detection range is determined from Eq (7) using a Hewlett-Packard model 9845 computer. Basically, the computer program (listed in the Appendix) iterates the difference between the left and right sides of Eq (7) by varying R until the difference is postive and less than 10^{-5}.

In the iterative process, the perceived range is corrected for blocking by the horizon. If the incremented range is less than the optical horizon, $R_o = 3.85 \sqrt{H_s}$, where H_s is the sensor height in metres, there is no blocking. If $R > R_o$ the target height used in the iteration process is

$$H_t' = H_t - H_{obsc} \tag{8}$$

where H_{obsc} is the obscuration height given by

$$H_{obsc} = \frac{(R - 3.85 \sqrt{H_s})^2}{14.8225} \tag{9}$$

III. AEROSOL EXTINCTION MODEL

The aerosol extinction model incorporated into SUBFLR was derived using the Navy aerosol size distribution model[2] developed at the Naval Research Laboratory for inclusion into LOWTRAN 6. The size distribution model (developed from empirical fits to a large data set of size distribution measurements in a variety of marine environments) is the sum of three log-normal distributions. Component one represents continental aerosols, and components two and three represent equilibrium sea spray particles generated by the 24-hour and instantaneous surface wind speeds, respectively, given by:

$$n(r) = \sum_{i=1}^{3} A_i \exp\left[-\left(\ln \frac{r}{fr_i}\right)^2\right], \quad cm^{-3}\ \mu m^{-1} \tag{10}$$

where $A_1 = 2000\ (AM)^2$

$A_2 = 5.866\ (W_o - 2.2)$

$A_3 = .01527\ (W' - 2.2)$

(AM) is an air mass parameter varying from a value of 1.0 for open ocean to a value of 10 in coastal areas. W_o and W' are the averaged 24-hour and instantaneous wind speeds, respectively. If W_o and W' are unknown the following zonal default values apply with $W_o = W'$:

a. Tropical = 4.1 m/s

b. Midlatitude summer = 4.1 m/s

c. Midlatitude winter = 10.3 m/s

d. Subarctic summer = 6.7 m/s

e. Subarctic winter = 12.4 m/s

Other default values are: if $5.866(W_o-2.2) < 0.5$ then $A_2 = 0.5$, and if $0.01527(W'-2.2) < 1.5 \times 10^{-5}$, then $A_3 = 1.5 \times 10^{-5}$.

In Eq (10) r_i, the modal radius for each distribution component, is allowed to grow with relative humidity (RH) according to

$$f = \left[\frac{(2 - RH/100)}{6(1 - RH/100)} \right]^{1/3} \tag{11}$$

The contribution to the total extinction by each component can be written as:

$$\beta_a(\lambda)_i = C_i \int_r Q_e(\lambda,r,m) \exp\left[-\left(\ln\frac{r}{fr_i}\right)^2\right] r^2 \, dr \tag{12}$$

where

$$C_i = \frac{0.001\pi}{f} A_i$$

The factor f^{-1} in the expression for C_i insures a constant total number of particles as the humidity increases. $Q_e(\lambda,r,\varepsilon)$ is the cross section for extinction normalized to the spherical particle geometrical cross section, and m is the complex refractive index at a wavelength λ. The refractive index is allowed to change[4] from that of a dry sea salt[5] as the particle deliquesces with increasing humidity.

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4. G. Hänel, "New Results Concerning the Dependence of Visibility on Relative Humidity and Their Significance in a Model for Visibility Forecast," Beiträge zur Physik der Atmosphäre, 44, 137-167, 1971.

5. F.E. Volz, "Infrared Refractive Index of Atmospheric Aerosol Substances," Appl. Opt., 11, 755-759, 1972.

The Navy model provides precalculated values of the parameters $\beta_a(\lambda)_i/C_i$ at discrete wavelengths for relative humidities of 50, 85, 95 and 99% from which the average extinction coefficient

$$\langle\beta_a\rangle_i = \frac{1}{\Delta\lambda} \int_\lambda \beta_a(\lambda)_i \, d\lambda \tag{13}$$

for a wavelength band $\Delta\lambda$ can be determined.

Shown in Fig 1 are the values of $\langle\beta_a\rangle_i/C_i$ calculated from the discrete wavelength values provided by the Navy model at the four relative humidities. Also shown are the least squares fit to the data points by the equation

$$\langle\beta_a\rangle_i/C_i = \frac{a_i}{100 - RH} + b_i \tag{14}$$

.he values of a_i and b_i determined from the regression analyses allow the 8-12 μm aerosol extinction coefficient to be written as:

$$\langle\beta_a\rangle = 2 \times 10^3 (AM)^2 \left(\frac{5.69 \times 10^{-7}}{100 - RH} + 1.66 \times 10^{-9}\right) +$$

$$5.86\ (W_o - 2.2) \left(\frac{4.13 \times 10^{-3}}{100 - RH} + 3.69 \times 10^{-5}\right) +$$

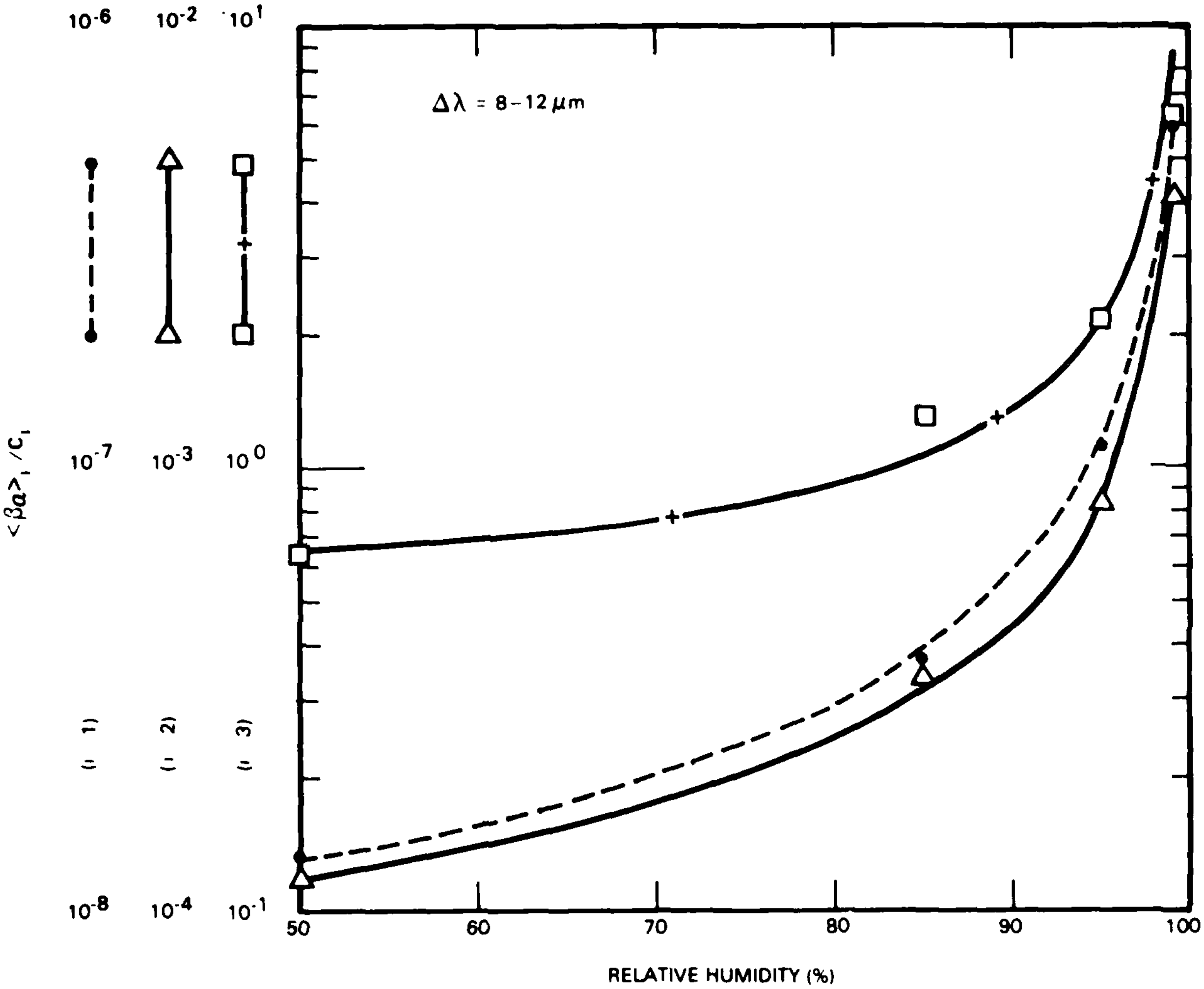

Figure 1. 8-12 μm band averaged values of $\langle\beta_a\rangle_i/C_i$ calculated from the Navy model at relative humidities of 50, 80, 95 and 99%. Connecting lines indicated least squares fit to the data point.

$$0.01527\ (W' - 2.2)\left(\frac{8.308}{100 - RH} + 0.491\right),\ km^{-1} \quad (15)$$

In a similar manner a relationship for the extinction coefficient at 0.55 µm is determined (see computer listing line 1040). If the visual range (visibility) R_v is known, the aerosol extinction coefficient can be normalized by the scaling factor:

$$V_{sf} = \frac{3.912}{R_v\ \beta_a(0.55\ \mu m)} \quad (16)$$

This normalization essentially adjusts the total number of particles to match the observed visibility. The above relationships apply to relative humidities between 50 and 99% and assume horizontal homogeneity. If the humidity is unknown a default value of 80% should be used.

IV. RANGE-DEPENDENT MOLECULAR ABSORPTION COEFFICIENT

In addition to water vapor absorption (band and continuum), molecular absorption in the 8-12 µm band is influenced by uniformly mixed atmospheric gases (CO_2, N_2, CH_4, CO, O_2, and O_3). If the absorber quantities along the path are known, the atmospheric transmittance can be determined for the path from the spectral absorption properties of the various absorbers. The total broadband transmittance is calculated by multiplying the individual transmittances of each contributing absorber averaged over a narrow spectral band, $\delta\lambda$, and integrating these composite results over the broad spectral band $\Delta\lambda$. Thus

$$\langle \tau_m(R) \rangle = \frac{1}{\Delta\lambda} \int_{\lambda} [\pi_j \; \bar{\tau}_j(R, \delta\lambda)] \, d\lambda \qquad (17)$$

The molecular absorption model employed in SUBFLR has been derived from the LOWTRAN 5 program of Kneizys et al[1]. The 8-12 μm band averaged absorption coefficients computed from $\langle \tau_m(R) \rangle$ of Eq (17) according to the relationship

$$\langle A_m(R) \rangle = - \frac{1}{R} \ln[\langle \tau_m(R) \rangle] \qquad (18)$$

are shown in Fig 2 as functions of range for differing absolute humidities. The curves of constant absolute humidity were computed for a surface level (constant pressure) path using several different temperatures and relative humidities. The contributions to transmittance by the uniformly mixed gases were accounted for by assuming absorber amounts equivalent to the 1962 Standard Atmosphere. The circled curves indicate different absorptions calculated with the same absolute humidity which resulted from different combinations of temperature and relative humidity. These differences in absorption are most likely caused by how the band and continuum contributions depend upon the actual temperature and relative humidity.

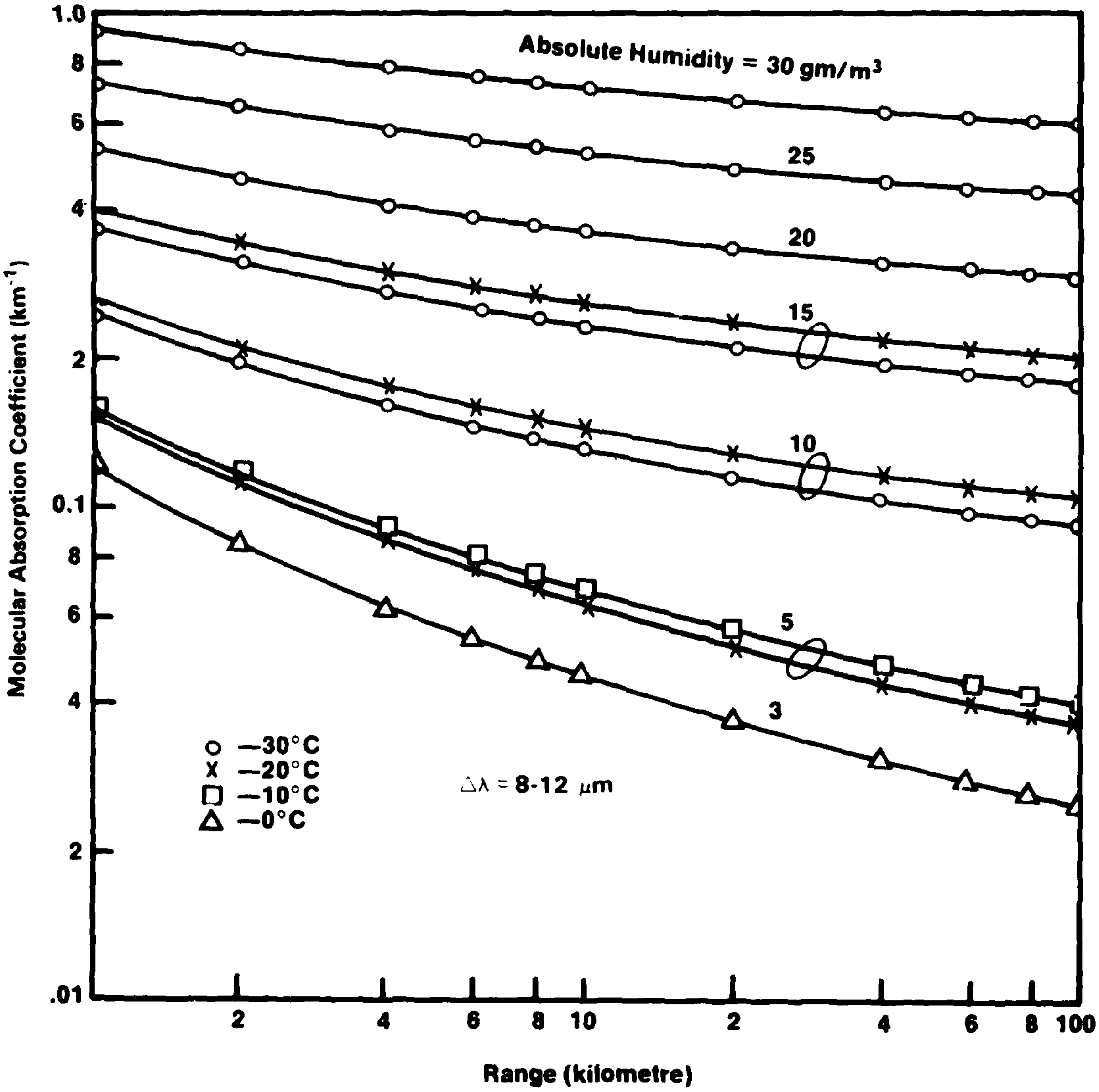

Figure 2. 8-12 μm band averaged absorption coefficient versus range for different absolute humidities.

In attempting to obtain a functional relationship for the absorption curves in Fig 2, it was found that the residuals of the least squares fit to the data were a minimum with the form

$$\langle A_m(R)\rangle = \alpha_o + \alpha_1 \log R + \alpha_2(\log R)^2 \tag{19}$$

where the coefficients α_o, α_1 and α_2 are functions of absolute humidity. Functional forms for the band-averaged absorption coefficient at specific ranges can also be derived, from which values of α_o, α_1, and α_3 can be determined for different absolute humidities. In Fig 3, the band-averaged absorption coefficients calculated at 1, 10 and 100 km are shown as a function of absolute humidity. The absorption coefficient at each range can now be represented in terms of absolute humidity, Ah, by a second-order polynomial equation of the form

$$B(R) = a_o + a_1(Ah) + a_2(Ah)^2 \tag{20}$$

where the coefficients determined for the three ranges are given in Table 1.

Table 1. Coefficients for three ranges.

Range (km)	a_o	a_1	a_2
1	8.0024E-2	1.2360E-2	5.3855E-4
10	1.5916E-2	7.8820E-2	4.9786E-4
100	4.8333E-3	4.7687E-3	4.8820E-4

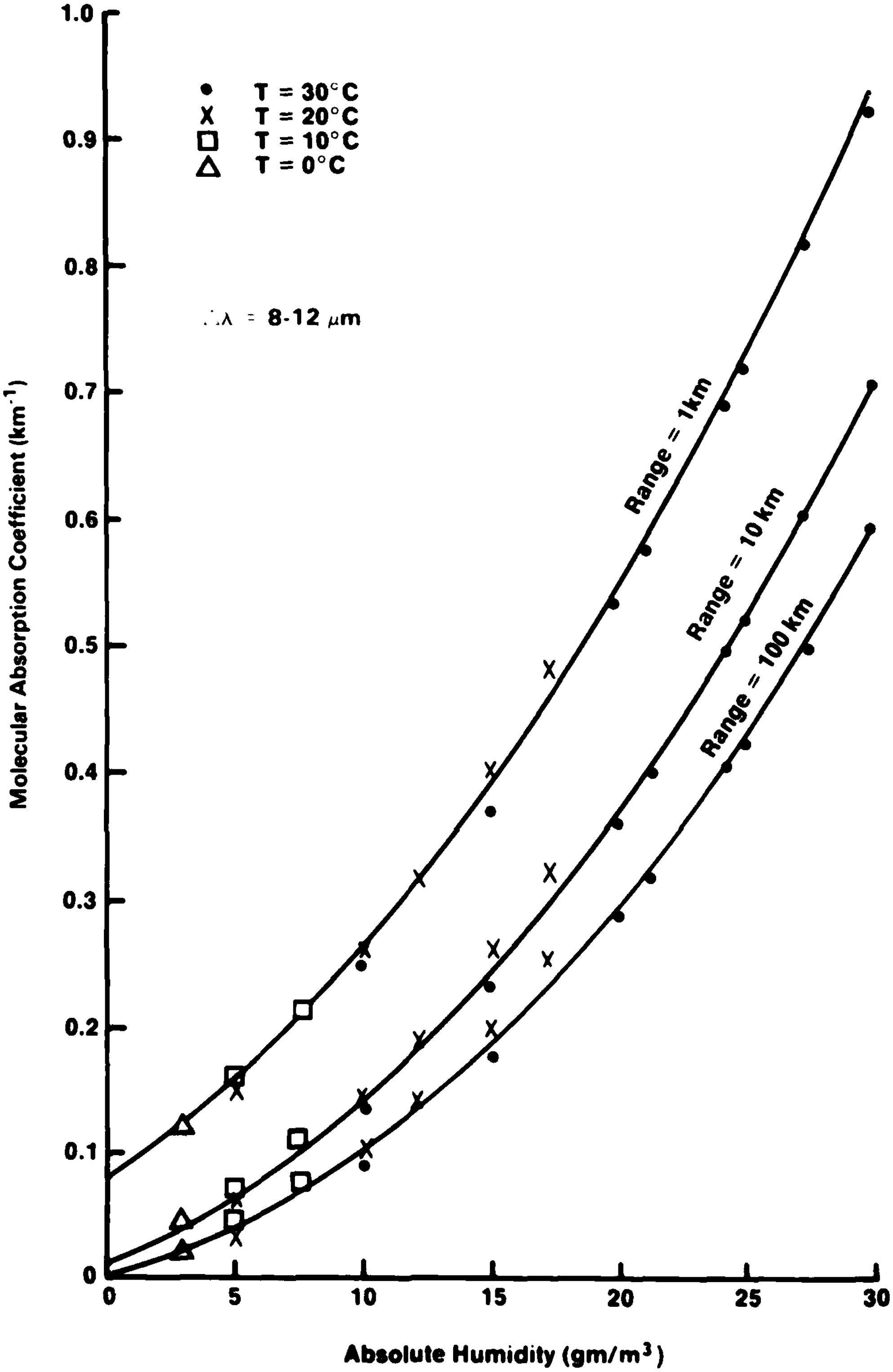

Figure 3. 8-12 μm band averaged molecular absorption coefficient versus absolute humidity at ranges of 1, 10 and 100 km.

Equating Eq (19) and (20) at each of the three ranges, the coefficients in Eq (19) can be determined as

$$\alpha_o = B_1 \qquad (20a)$$

$$\alpha_1 = B_2 - \alpha_o - \alpha_2 \qquad (20b)$$

$$\alpha_2 = B_3 - 2B_2 + B_1 \qquad (20c)$$

where B_1, B_2, B_3 correspond to the values of B(R) at 1, 10 and 100 km, respectively.

V. SAMPLE OUTPUT

After the program is loaded into memory, the HP-9845 computer interactively queries the user for the required inputs. As the asked-for inputs are typed in, the "CONTINUE" key is pressed for sequencing to the next input and initiating the range calculation and display/print-out. A sample printout for a current-generation FLIR operating against a large cruiser in the open ocean is shown below. The meteorological parameters, temperature difference and sensor height were arbitrarily chosen and resulted in a 50% probability detection range of 14.93 km. In this case the horizon obscured 4.6 m of the target's 19-m height.

(sample computer printout)

```
--------------------------------------------------------------------------------
        NEAR SURFACE, HORIZONTAL DETECTION RANGE CALCULATION
--------------------------------------------------------------------------------
AM= 1
Wind 24 Hr Ave.= 4.1 M/S Wind Inst.= 4.1  M/S Visibility=15.0 km.
Delta T= 3.0 C  FLIR Ht=  3.0 Metres CONST. 1 =2.036E-01 CONST. 2 =1.568E-01
Rh=80.0 Temp.=16.0 Deg. C Ah=10.9 Gm/M^3 Aero Ext= .170
Target Height= 19.00 Width=160.00 Metres

TOTAL EXT=4.601 RANGE= 14.4 KM OR   7.8 NM
Obscuration=  4.1 Metres Effective Target Height=14.93 Metres
--------------------------------------------------------------------------------
```

REFERENCES

1. F.X. Kneizys, E.P. Shettle, W.O. Gallery, J.H. Chetwynd, Jr., L.W. Abreu, J.E.A. Selby, R.W. Fenn and R.A. McClatchey, "Atmospheric Transmittance/Radiance: Computer Code LOWTRAN 5," AFGL-TR-80-0067, 21 February 1980.

2. Private communications, Stuart G. Gathman, Code 4320, Naval Research Laboratory.

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4. G. Hänel, "New Results Concerning the Dependence of Visibility on Relative Humidity and Their Significance in a Model for Visibility Forecast," Beiträge zur Physik der Atmosphäre, 44, 137-167, 1971.

5. F.E. Volz, "Infrared Refractive Index of Atmospheric Aerosol Substances," Appl. Opt., 11, 755-759, 1972.

APPENDIX

SUBFLR Program Listing

18 blank

```
10   OPTION BASE 1 !Name**SUBFLR***15 SEPT. 1982  **MRP**
20   ! MODIFIED TO CALC EXT. IN SUBROUTINE "Hughes" 31 Aug. 1982
30   ! -----------------------------------------------------------------
40   ! **This program requires the input of the various FLIR parameters as well
50   ! as the target-to-background temperature difference. Designed for surface
60   ! detection ranges. Allows for target obscuration for beyond the horizon
70   ! conditions.
80   ! ------------------------------------------------------------------
-
90   PRINTER IS 0
100  PRINT CHR$(27)&"&120T"
110  PRINTER IS 16
120  INPUT "PRINTER SELECTION, P for printer, S for screen",X$
130  IF X$="P" THEN PRINTER IS 0
140  IF X$="S" THEN PRINTER IS 16
150 PRINT "  ---------------------------------------------------------------
---------"
160 PRINT TAB(11);"NEAR SURFACE, HORIZONTAL DETECTION RANGE CALCULATION"
170 PRINT "  ---------------------------------------------------------------
---------"
180 Start: ! + + + + + + + + + + + + + + + + + + + + + +
190  RAD
200  ! + + + + + + + + + + + + + + + + + + + + + + +
210 Hrange: ! *  Calculates horizontal detection range from FLIR to target. Uses
 range dependent molecular extinction.
220  ! ********
230  INPUT "DELTA T(C), SENSOR HEIGHT(Metres)",Tdiff,Hsensor
240  INPUT "SYSTEM CONSTANTS C1,C2",Cs1,Cs2
250  INPUT "RH,TEMP.(DEG. C)",Rx,Temp
260  GOSUB Hughes
270  Aer1=Betair
280  PRINT USING 290;Tdiff,Hsensor,Cs1,Cs2
290  IMAGE 2X,"Delta T=",DD.D," C  FLIR Ht=",DDD.D," Metres CONST. 1 =",D.DDDE,
" CONST. 2 =",D.DDDE
300  GOSUB Abshum
310  PRINT USING 320;Rx,Temp,Ah,Aer1
320  IMAGE 2X,"Rh=",DD.D," Temp.=",DD.D," Deg. C Ah=",DD.D," Gm/M^3 Aero Ext=",D
.DDD," Mol. Ext.="D.DDD
330  INPUT "Target Height,Width in metres",Htarget,W
340  PRINT USING 350;Htarget,W
350  IMAGE 2X,"Target Height=",DDD.DD," Width=",DDD.DD" Metres"
360  R=0
370  Rd=1
380  ! ------------------
390 Loop:  R=R+Rd      !--
400  ! ------------------
410  Hobsc=(R-3.85*SQR(Hsensor))^2/14.8225
420  IF R<3.85*SQR(Hsensor) THEN Hobsc=0
430  H=Htarget-Hobsc
440  DISP ,Hobsc,H
450  GOSUB Rmolec
460  T=Aer1+Amol
470  IF H<=0 THEN Overhoriz
480  A1=Tdiff*EXP(-T*R)
490  New=R/SQR(H*W)/2
500  A2=Cs1*New*SQR(1+Cs2*New^2)
510  A=A1-A2
520  IF A<0 THEN GOSUB Rdel
530  IF (A>0) AND (A<.00001) THEN GOTO Prntout
540  GOTO Loop
550  PRINT TAB(3),"----------------------------------------------------------
---------------"
560  GOTO Start
570  ! *************
580 Rdel:  !        *
590  ! *************
600  R=R-Rd
610  Rd=Rd/10
```

```
620  RETURN
630  ! *********
640 Abshum: !  *
650  ! *********
660  Q=18/8.315
670  Esat=6.105*EXP(25.22*(Temp/(Temp+273.2))-5.31*LOG(1+Temp/273.2))
680  Abhum=Rx*Esat*Q/(273.2+Temp)
690  Ah=Abhum
700  RETURN
710  ! **********
720 Prntout: !  *
730  ! **********
740  Xttl=R*T
750  Rnm=R/1.853
760  PRINT
770  PRINT USING 780;Xttl,R,Rnm
780  IMAGE 2X,"TOTAL EXT=",D.DDD," RANGE=",DDD.D," KM OR ",DDD.D," NM"
790  PRINT USING 800;Hobsc,H
800  IMAGE 2X,"Obscuration=",DDD.D," Metres Effective Target Height=",DD.DD," Me
tres"
810  GOTO 550
820  ! ************
830 Rmolec: !
840  ! ************
850  B1=8.0024E-2+1.236E-2*Ah+5.3855E-4*Ah*Ah
860  B2=1.5916E-2+7.882E-3*Ah+4.9786E-4*Ah*Ah
870  B3=4.8333E-3+4.7687E-3*Ah+4.8820E-4*Ah*Ah
880  Alpha0=B1
890  Alpha2=(B3-2*B2+B1)/2
900  Alpha1=B2-Alpha0-Alpha2
910  Amol=Alpha0+Alpha1*LGT(R)+Alpha2*LGT(R)^2
920  RETURN
930 Hughes: ! Calculates aerosol extinctions per NRL equations. 31 Aug. 1982
940   INPUT "AM (1-10)",Am
950   PRINT "  AM=";Am
960  Rx1=100-Rx
970  INPUT "24 Hour Wind speed ave. Metres/sec.",W0
980  INPUT "Current measured wind speed Metres/sec.",Ws
990  C2=5.866*(W0-2.2)
1000 C3=.01527*(Ws-2.2)
1010 IF C2<.5 THEN C2=.5
1020 IF C3<1.4E-5 THEN C3=1.4E-5
1030 ! ---CALC. EXTINCTION AT 0.55 -------
1040 Beta55=(4.74E-2/Rx1+2.9E-4)*Am*Am+C2*(1.48E-2/Rx1+9.08E-4)+C3*(7.73/Rx1+.42
8)
1050 INPUT "Visual Range in km. if unknown input -1",Rv
1060 IF Rv>0 THEN Vsf=3.912/(Rv*Beta55)
1070 IF Rv<0 THEN Vsf=1
1080 ! --CALC. IR EXTINCTION ---------
1090 A1=(1.138E-3/Rx1+3.32E-6)*Am*Am
1100 A2=(4.13E-3/Rx1+3.69E-5)*C2
1110 A3=(8.308/Rx1+.491)*C3
1120 Betair=(A1+A2+A3)*Vsf
1130 PRINT USING 1140;W0,Ws,Rv
1140 IMAGE 2X,"Wind 24 Hr Ave.=",DD.D," M/S Wind Inst.=",DD.D,"  M/S Visibility=
",DD.D," km."
1150 RETURN
1160 Overhoriz:! ***********
1170 PRINT
1180 PRINT "TARGET IS OVER THE HORIZON, OUT OF VIEW"
1190 PRINT " ------------------------------------------------------------------
-----------"
1200 GOTO Start
1210 END
```

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