NASA Technical Memorandum 100710

Atmospheric Transmission Coefficients for Laser Pulses with Spectral Widths of a Few Tenths of a Nanometer, Over the Wavelength Region from 800 to 860 Nanometers

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JULY 1988

NASA

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INTRODUCTION

For laser communication experiments between space and ground terminals, the spectral width of the optical source can have a significant effect on the atmospheric transmission. The spectral width of a pulsed source depends both on the temporal length of the pulse and on the frequency stability of the laser, and also on the frequency spread between lasers if more than one laser is used to achieve the desired transmitter power.

In the 800 to 860-nanometer spectral region, the atmospheric absorption lines (almost entirely water lines) have linewidths of a few hundredths of a nanometer. Thus, for a laser pulse with a spectral width of several tenths of a nanometer, such as those produced by AlGaAs laser diode arrays, the total atmospheric transmission cannot be accurately computed by using the transmission coefficient at a single wavelength. In such cases, it becomes necessary to take a weighted average over the pulse spectral width, with the weights dependent on the pulse spectral shape. The effective transmission coefficient thus computed will depend on the pulse's center wavelength and on its spectral width and shape.

In this report, the effective atmospheric transmission coefficient is computed as a function of the pulse center wavelength over the wavelength region from 800 to 860 nanometers. The computations were performed for several pulse spectral widths and for a gaussian spectral shape. Computations were also performed for a spectrally flat pulse to evaluate the sensitivity of the spectra to the pulse shape. It turns out that the flat-pulse spectra differ only slightly from the gaussian-pulse spectra, which indicates that the exact pulse shape is not critical.

The single-wavelength (zero spectral width) transmission spectrum over the 800 to 860-nanometer region is computed in a line-by-line manner. The absorption line catalog used is the 1982 edition of the absorption line tape compiled by the Air Force Geophysics Laboratory, which lists all the known absorption lines for the seven most important atmospheric absorbing species, from the microwave region to the visible region (References 1 through 5). The computer program used to perform the calculations is described in Reference 6.

As would be expected, the effective atmospheric transmission spectrum becomes progressively smoother as the spectral width of the pulse increases, so that in general, a spectrally wide signal suffers less energy loss as it traverses the atmosphere than does a spectrally narrow signal. Thus, the use of a wider pulse may give greater flexibility in choosing the operating frequency of a direct detection laser communication system.

ANALYSIS

Let $e(\lambda)$ denote the energy spectrum of the pulse in the absence of atmospheric attenuation, where λ is the wavelength. Then, if $t(\lambda)$ denotes the transmission coefficient at the wavelength λ, the total received pulse energy is given by:

$$\text{Received pulse energy} = \int_{\text{PULSE}} e(\lambda)t(\lambda)\, dt. \tag{1}$$

If this is equated to the energy that would be received in the absence of atmospheric attenuation multiplied by an effective pulse transmission coefficient t_{eff}, then the effective coefficient may be written as

$$t_{\text{eff}} = \frac{\displaystyle\int_{\text{PULSE}} e(\lambda)t(\lambda)\, d\lambda}{\displaystyle\int_{\text{PULSE}} e(\lambda)\, d\lambda}. \tag{2}$$

Clearly, the actual energy e is not important; the energy will therefore be normalized relative to its value at the pulse center frequency. Thus, if the quantity $s = e(\lambda)/e(\lambda_c)$, then the above equation may be written as

$$t_{\text{eff}} = \frac{\displaystyle\int_{\text{PULSE}} s(\lambda)t(\lambda)\, d\lambda}{\displaystyle\int_{\text{PULSE}} s(\lambda)\, d\lambda}, \tag{3}$$

where $s(\lambda)$ may be regarded as the pulse spectral shape.

DESCRIPTION OF COMPUTER PROGRAM

To compute the integrals in Equation 3, it is sufficiently accurate to use a simple trapezoidal rule; thus, the effective coefficient may be approximated by:

$$t_{\text{eff}} \cong \frac{\sum \frac{1}{2}(s_n t_n + s_{n+1}t_{n+1})\cdot(\lambda_{n+1} - \lambda_n)}{\sum \frac{1}{2}(s_n + s_{n+1})\cdot(\lambda_{n+1} - \lambda_n)} \tag{4}$$

where s_n and t_n denote $s(\lambda_n)$ and $t(\lambda_n)$, respectively, and the summation is taken over a grid of points λ_n which spans the spectrum of the pulse (and need not be equally spaced). The grid of points is constructed by taking an equally spaced grid, with a spacing small enough to cover each absorption line by several points, and then adding to the grid the centers of the absorption lines, to ensure that the bottoms of the lines are not skipped over.

Two lineshapes are used in the calculations: a flat (constant) shape, and a gaussian shape. For the gaussian shape, the grid of points extends two halfwidths to either side of the line center.

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To calculate an effective atmospheric transmission spectrum for a given pulse shape and width, a grid of points is constructed as described above, spanning the entire wavelength region from 800 to 860 nanometers, by taking an equally spaced grid and intercalating the center wavelengths of all the absorption lines. The center wavelength of the pulse is then stepped along this grid; at each point, the effective transmission coefficient of the pulse is computed from Equation 4.

The computed transmission coefficients are stored in a disk file for later plotting. Some representative plots are shown in the next section of this report.

PLOTS OF EFFECTIVE ATMOSPHERIC TRANSMISSION

Due to the large amount of spectral detail in the 60-nanometer-wide region considered in this report, the plots of the effective transmission spectra are divided into three subregions, each 20 nanometers wide.

Figures 1, 2 and 3 show the effective transmission spectra over these three subregions, for pulses having a gaussian spectral shape and spectral widths (full width at half maximum) of 0.1, 0.3 and 0.5 nanometers. In each plot, the single-wavelength transmission spectrum (which may be regarded as the spectrum for pulses of zero spectral width) is also shown. From these three plots it is seen that the spectrum is quite flattened out for pulses which are 0.5 nanometers wide.

Figure 4 shows a portion of the same spectra, over the smaller region from 815 to 820 nanometers (with an expanded scale), to more clearly show the details of the spectra. The computer program is capable of plotting the spectra over any subregion.

Figure 5 shows the spectra for 0.1, 0.3 and 0.5-nanometer-wide pulses, with both gaussian and flat spectral shapes, over the 815 to 820-nanometer region. While the spectra for the two shapes are noticeably different, the differences are relatively minor, which indicates that the transmission spectrum is not very sensitive to the exact spectral shape of the pulse.

Figure 1. Transmission Spectra for Laser Pulses of Various Spectral Widths—Region 1
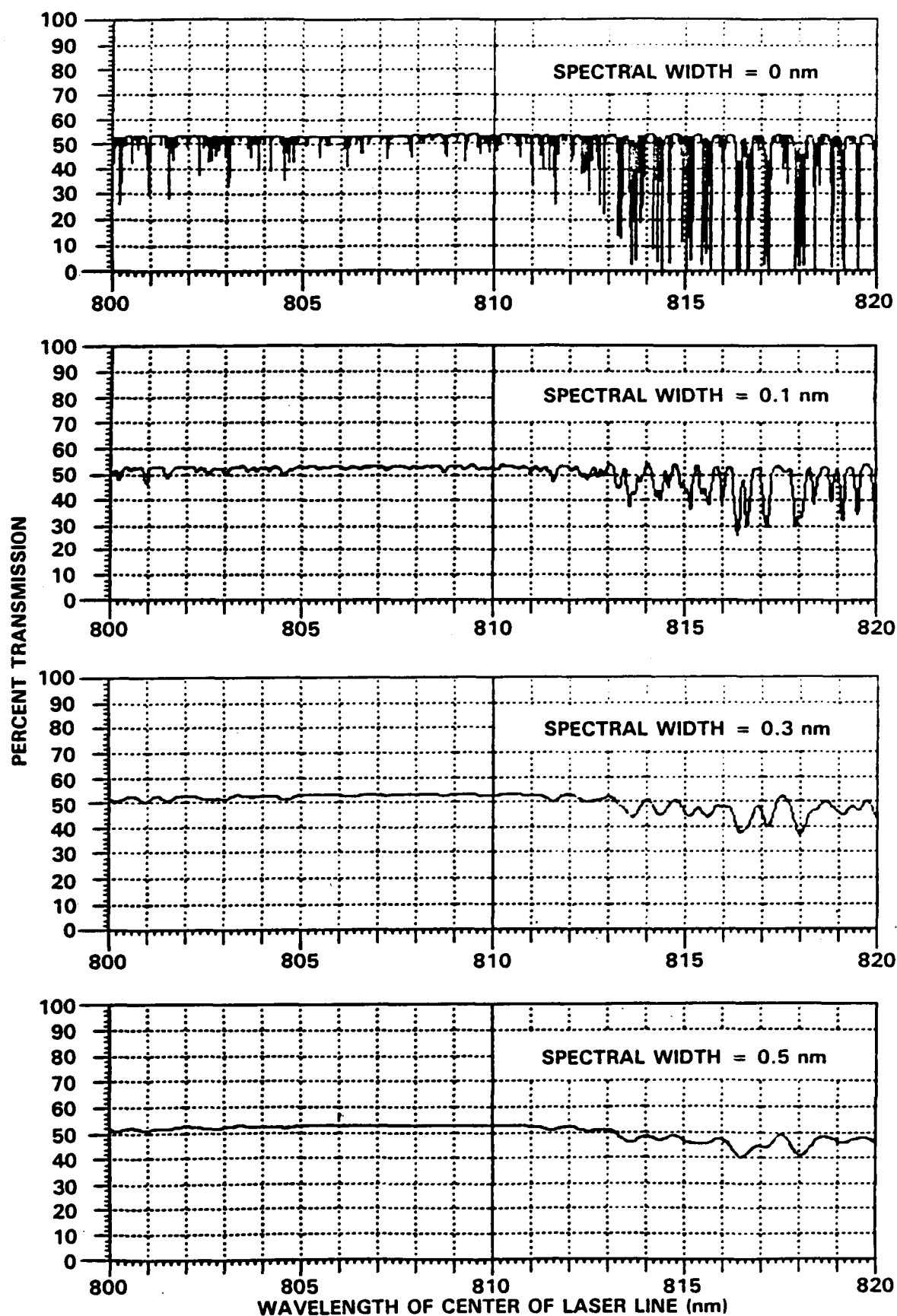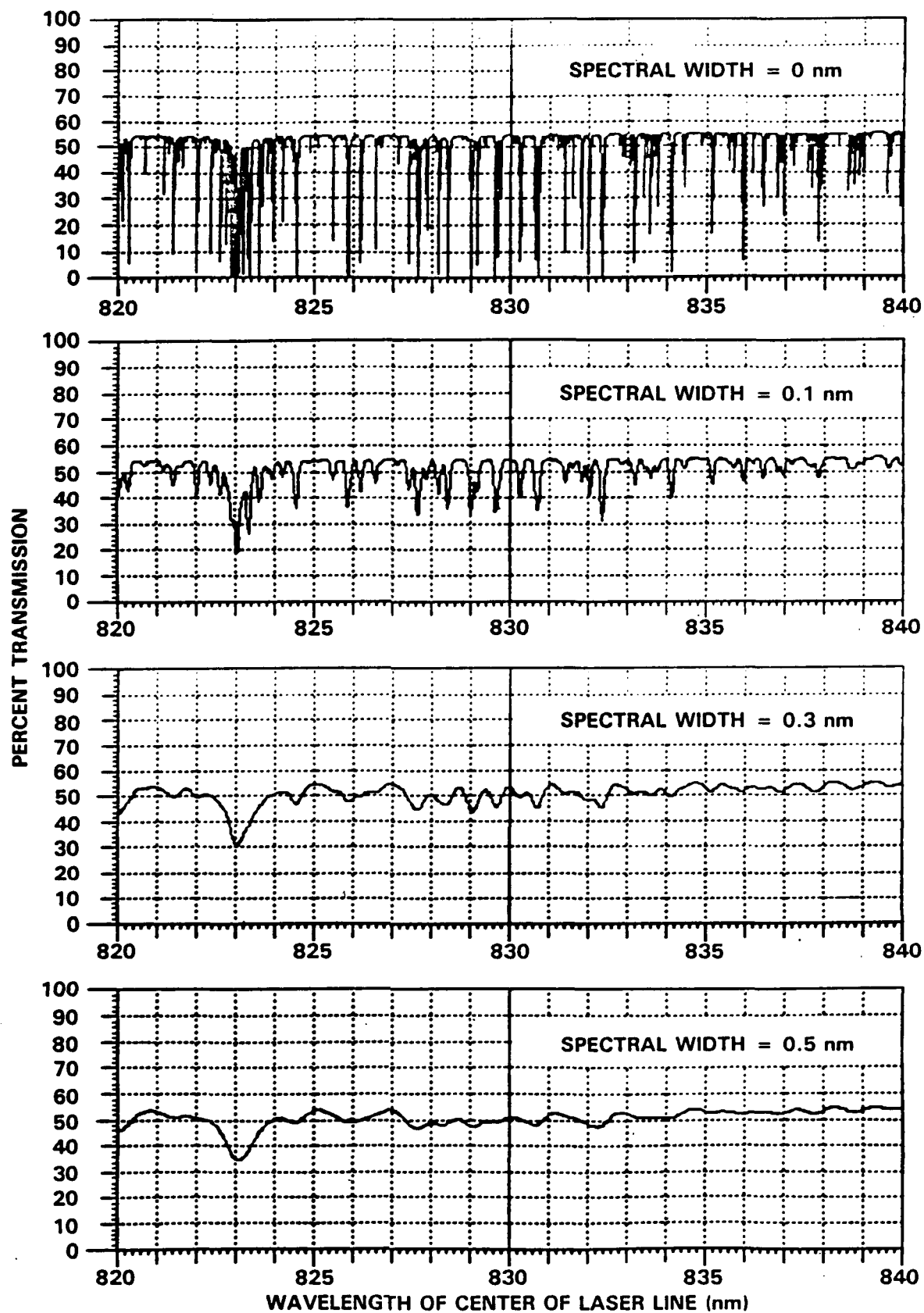
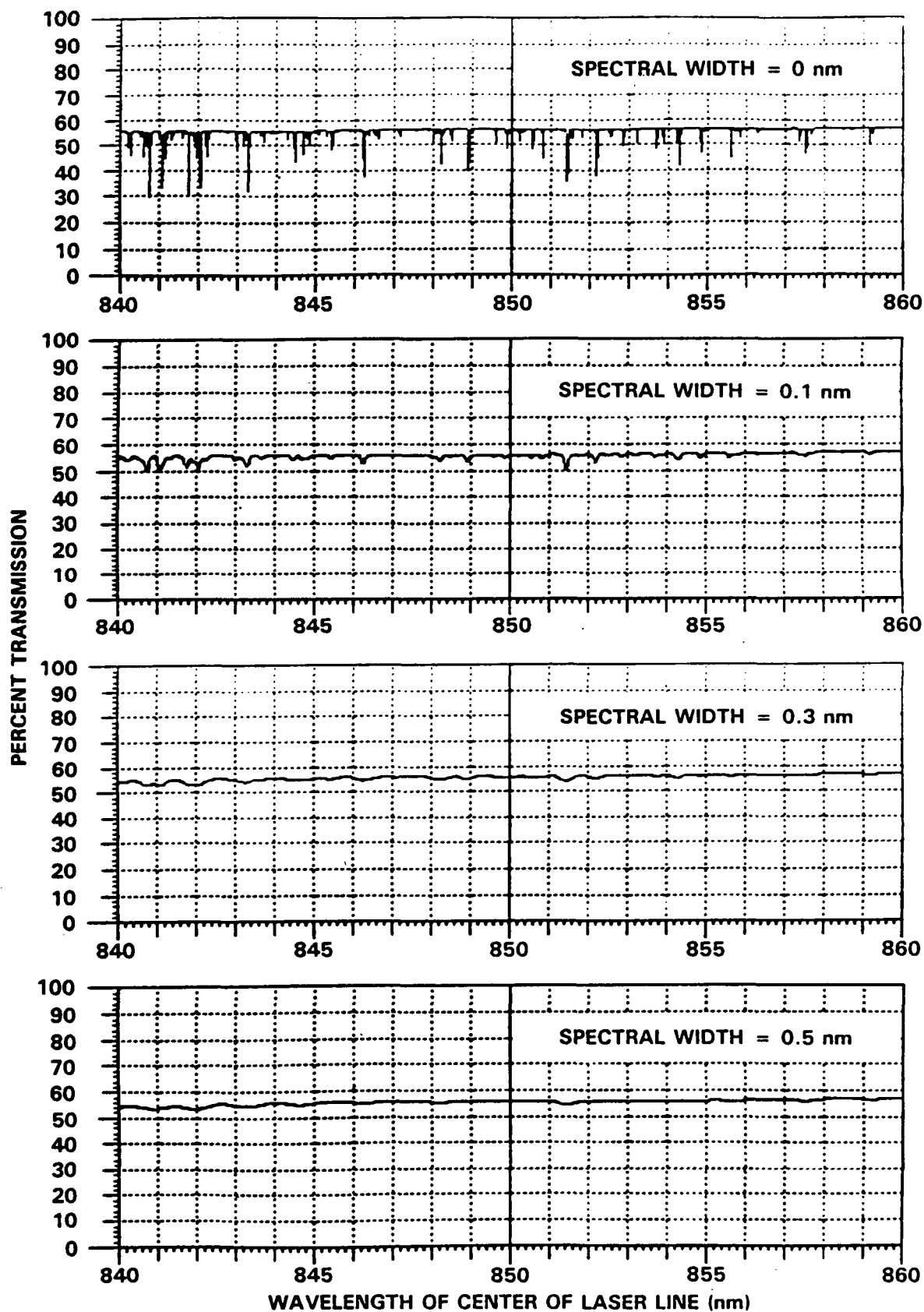Figure 2. Transmission Spectra for Laser Pulses of Various Spectral Widths—Region 2

Figure 3. Transmission Spectra for Laser Pulses of Various Spectral Widths—Region 3
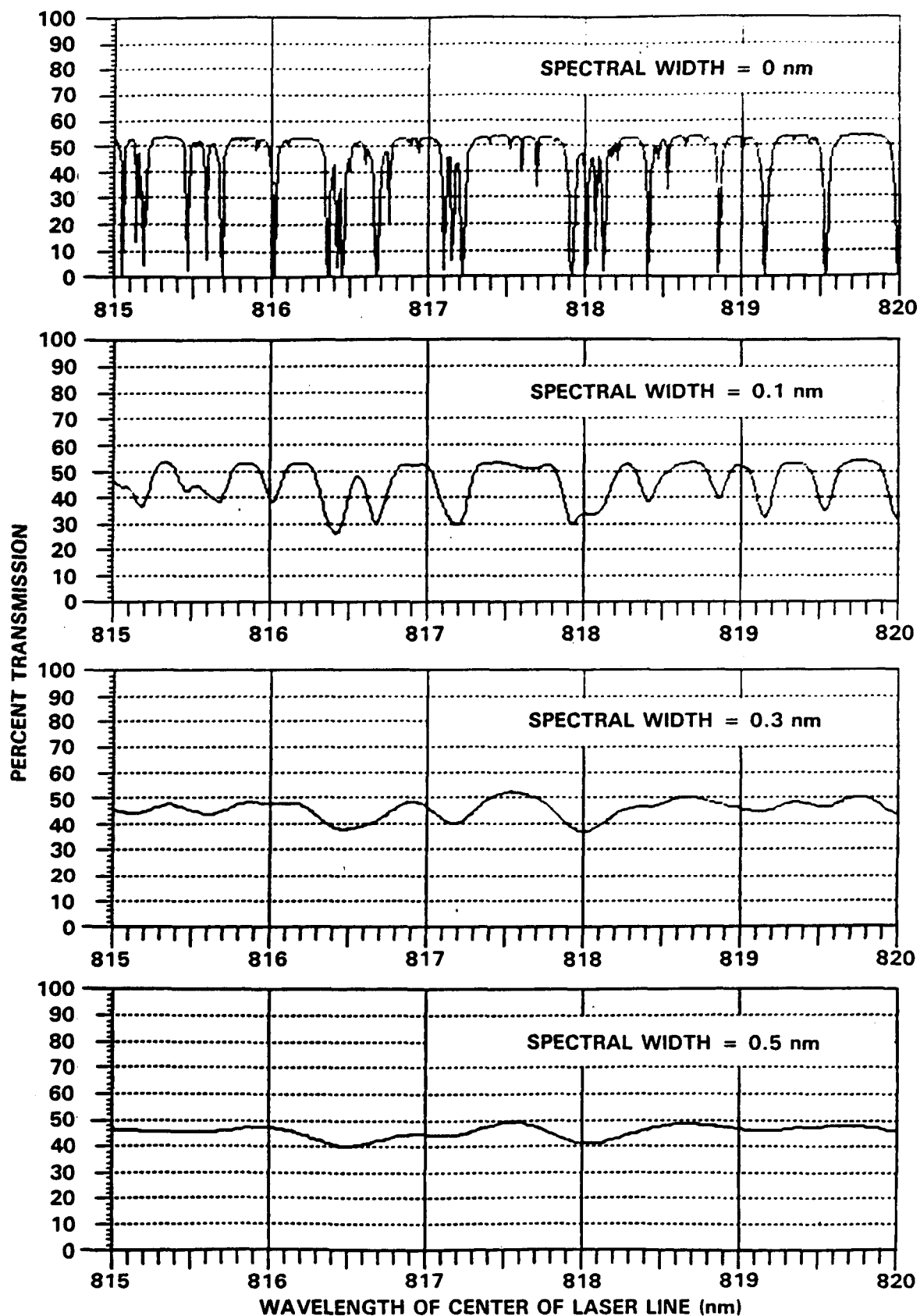
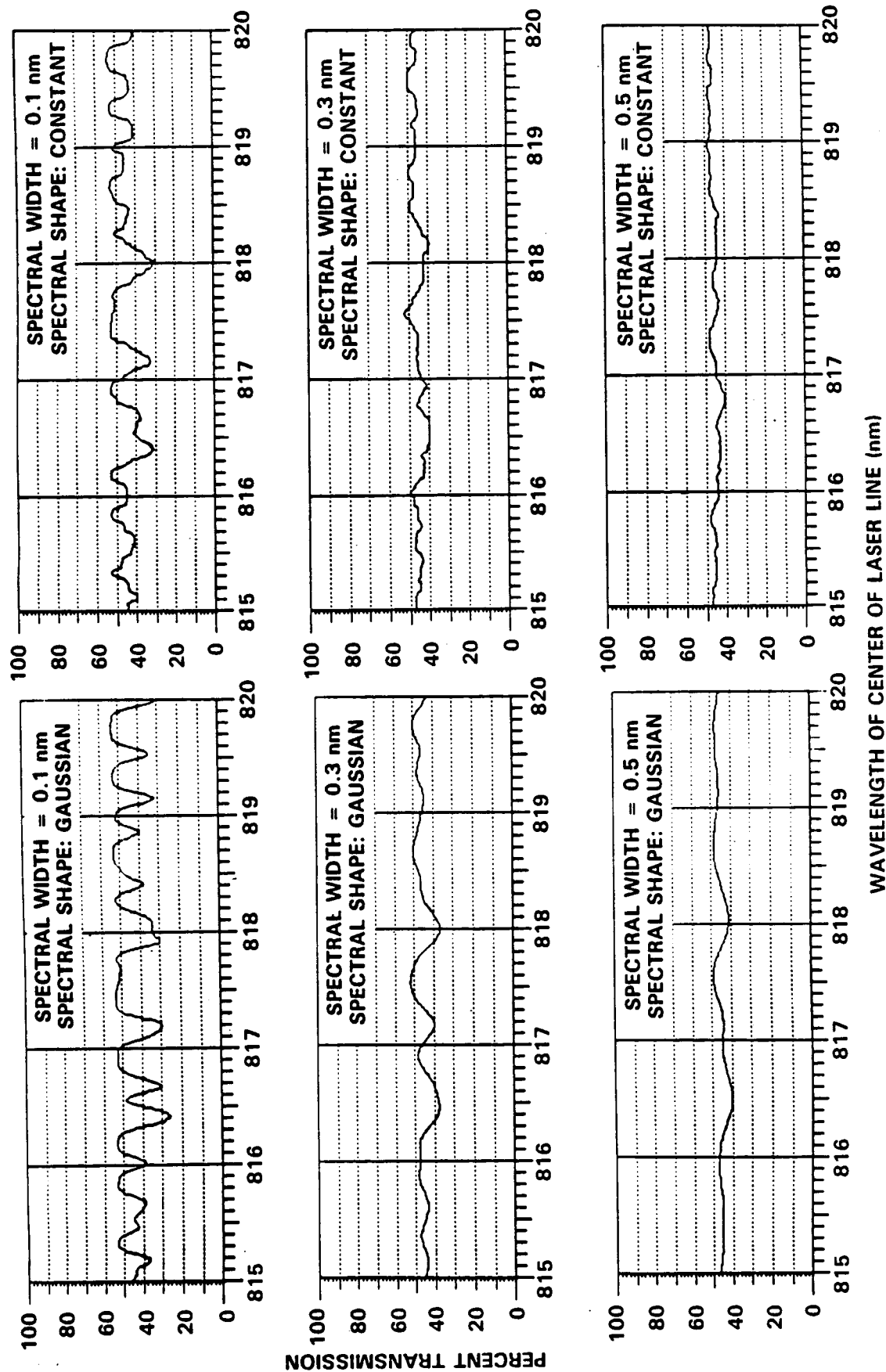Figure 4. Transmission Spectra for Laser Pulses of Various Spectral Widths—Expanded Subregion of Region 1

Figure 5. Comparison of Transmission Spectra for Laser Pulses of Two Different Spectral Shapes

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SUMMARY AND CONCLUSIONS

Calculations were made to determine the effective transmission spectra, over the wavelength region from 800 to 860 nanometers, for laser pulses with spectral widths of 0.1, 0.3 and 0.5 nanometers.

Several conclusions may be drawn from the results of this study:

1. For laser pulses with spectral widths of several tenths of a nanometer, the effect of atmospheric absorption lines depends on the spectral width of the pulse;
2. Atmospheric water vapor absorption lines can be very deep, but they are only a few hundredths of a nanometer wide in this region of the spectrum, so that laser diode transmitters may not be severely affected even if they are centered on a line, or overlap one or more lines;
3. Pulse spectral widths of several tenths of a nanometer may reduce atmospheric absorption by water lines to as little as 10 or 20 percent, even when the laser is centered on a line (the remaining extinction of about 50 percent shown in the plots is due mainly to aerosol absorption and scattering); and
4. The pulse spectral shape appears to have a rather minor effect on the transmission spectrum. (The spectra for flat pulses are somewhat more jagged than those for gaussian pulses, which might be expected because the flat pulse, as it is moved along the wavelength axis, includes and excludes absorption lines much more suddenly than does a gaussian pulse, with its long tails.)

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3. Rothman, L.S. "Update of the AFGL Atmospheric Absorption Line Parameters Compilation", Applied Optics letter, Vol. 17, No. 22, 15 November 1978.

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PROGRAM SMOOTH

```
C
C This routine takes a transmission spectrum, in which each value is the
C transmission coefficient at that exact wavelength (in Angstroms, for this
C routine), and replaces that value by the effective transmission coefficient
C for a laser line of finite width (with a constant or gaussian spectral
C shape) centered at the given wavelength. The resulting spectrum is a
C "smoothed" spectrum for the effective transmission coefficient.
C
C*******************************************************************************
C
        BYTE        INFILE(15), OUTFIL(15), VMFILE(15),
     *              SHAPE, GAUSS, CONST
C
        INTEGER*2   DATCNT
C
        REAL*4      LOWERW, WAVLEN, TRANS
C
        DATA        INFILE/15*'000/, OUTFIL/15*'000/, VMFILE/15*'000/,
     *              GAUSS/'G'/, CONST/'C'/
C
C*******************************************************************************
C
C       Ask user for the spectrum file to be "smoothed"
C       - - - - - - - - - - - - - - - - - - - - - - - - -
C
C
        TYPE 100
100     FORMAT(//t2,'Transmission spectrum file to be "smoothed":   ',$)
        ACCEPT 101, INFILE
101     FORMAT(15A1)
C
C
C       Ask user for the name of the "smoothed" file
C
C       - - - - - - - - - - - - - - - - - - - - -
C
        TYPE 200
200     FORMAT(//t2,'Name of file to hold the "smoothed" spectrum:   ',$)
        ACCEPT 101, OUTFIL
C
C
C       Ask user for the lineshape
C       - - - - - - - - - - - - -
C
        TYPE 250
250     FORMAT(//t2,'Lineshape — gaussian or constant (G or C)? ',$)
        ACCEPT 251, SHAPE
251     FORMAT(A1)
C
```

```
C
C       Ask user for the laser line width
C       - - - - - - - - - - - - - -
C
        TYPE 300
    300 FORMAT(//
      *         t2,'Halfwidth (at halfmax for gaussian shape)'/
      *         t2,'of laser line, in Angstroms:   ',$)
        ACCEPT 301, HWIDTH
    301 FORMAT(F6.2)
C
C
C       Open the input and output files;
C       copy the header information to the output file.
C       - - - - - - - - - - - - - - - - - - - - - - - -
C
        OPEN (UNIT=1, NAME=INFILE, TYPE='OLD', DISP='KEEP',
      *         FORM='UNFORMATTED', RECORDSIZE=2)
C
        OPEN (UNIT=2, NAME=OUTFIL, TYPE='NEW', DISP='KEEP',
      *         FORM='UNFORMATTED', RECORDSIZE = 2, INITIALSIZE = 100)
C
        READ(1)    PLTCOD,    ANGMIC
        READ(1)    LOWERW,    UPPERW
        READ(1)    ATL,       ATU
        WRITE(2)   PLTCOD,    ANGMIC
        WRITE(2)   LOWERW,    UPPERW
        WRITE(2)   ATL,       ATU
C
C
C       Open a direct access working file in VM to hold a
C       copy of the input file. Copy the rest of the input file
C       (the data points) to the VM file; count the number of
C       data points.
C       - - - - - - - - - - - - - - - - - - - - - - - - - -
C
        OPEN (UNIT=3, NAME='VM:WORK.DAT', TYPE='NEW', DISP='DELETE',
      *         ACCESS='DIRECT', FORM='UNFORMATTED', RECORDSIZE=2,
      *         INITIALSIZE=100)
C
        ICOUNT = 0
    400 READ(1,END=450) WAVLEN, TRANS
        ICOUNT = ICOUNT+ 1
        WRITE(3'ICOUNT) WAVLEN, TRANS
        GO TO 400
C
    450 DATCNT = ICOUNT
        CLOSE (UNIT=1, DISP='KEEP')
C
C
C       Position laser lineshape at high wavelength end of spectrum,
C       so that its high-wavelength, two-halfwidth point "hits" the
C       upper edge of the data region (recall that the spectrum is
```

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```
C       stored "backwards" in the files, from high to low wavelengths)
C       ---------------------------------------------------
C
C

        READ (3'1) WAVLEN, TRANS
        NHIGH = 1
        AHIGH = WAVLEN
        ACENTR =WAVLEN - 2.*HWIDTH
C
        NCENTR = 2
   500 IF (NCENTR .GT. DATCNT)  GO TO 5000
        READ (3'NCENTR) WAVLEN,TRANS
        IF (WAVLEN .LE. ACENTR)  GO TO 510
        NCENTR = NCENTR + 1
        GO TO 500
C
   510 ACENTR = WAVLEN
        ALOW = ACENTR - 2.*HWIDTH
        NLOW = NCENTR + 1
   520 IF (NLOW .GT. DATCNT)  GO TO 5000
        READ (3'NLOW)  WAVLEN, TRANS
        IF (WAVLEN .LE. ALOW)  GO TO 530
        NLOW = NLOW + 1
        GO TO 520
C
   530 ALOW = WAVLEN
C
C
C       Step laser lineshape along the grid of points;
C       at each step, compute the effective transmission coefficient.
C       ---------------------------------------------------
C
C
  1000 NCENTR =NCENTR + 1                    ! Next center point
        READ (3'NCENTR)  WAVLEN, TRANS
        ACENTR = WAVLEN
C
  1100 NHIGH = NHIGH + 1                     ! Next high point
        READ (3'NHIGH)  WAVLEN, TRANS
        IF ((WAVLEN-ACENTR) .LE. 2.*HWIDTH)  GO TO 1150
        GO TO 1100
C
  1150 NHIGH = NHIGH - 1
        IF (NHIGH .EQ. 1)  NHIGH = 2         ! MUST have NHIGH .GE. 2
        READ (3'NHIGH)  WAVLEN, TRANS
        AHIGH = WAVLEN
C
  1200 NLOW = NLOW + 1                       ! Next low point
        IF (NLOW .GT. DATCNT)  GO TO 5000
        READ (3'NLOW)  WAVLEN, TRANS
        IF ((ACENTR-WAVLEN) .LE. 2.*HWIDTH)  GO TO 1220
        IF ((ACENTR-WAVLEN) .GT. 2.*HWIDTH)  GO TO 1230
C
  1220 NLOW = NLOW + 1
```

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```fortran
      IF (NLOW .GT. DATCNT)  GO TO 5000
      READ (3'NLOW)  WAVLEN, TRANS
      IF ((ACENTR-WAVLEN) .LE. 2.*HWIDTH)  GO TO 1220
      ALOW = WAVLEN
      GO TO 1300
C
 1230 NLOW = NLOW - 1
      READ (3'NLOW)  WAVLEN, TRANS
      IF ((ACENTR-WAVLEN) .GT. 2.*HWIDTH)  GO TO 1230
      NLOW = NLOW + 1
      READ (3'NLOW)  WAVLEN, TRANS
      ALOW = WAVLEN
C
 1300          SUMNUM = 0.                    ! Calculate sums
      SUMDEN             = 0.
C
      DO 1350 I=1,NLOW-NHIGH+1
      II = I
      N = NLOW - (II-1)
      READ (3'N)      WAVLEN, TRANS
      READ (3'N-1)    WVNEXT, TRNEXT
      IF (SHAPE .EQ. GAUSS)  GO TO 1310
      IF (SHAPE .EQ. CONST)  GO TO 1315
C
 1310 EXPN   = ((WAVLEN-ACENTR)/HWIDTH)**2 * ALOG(0.5)
      EXPN1  = ((WVNEXT-ACENTR)/HWIDTH)**2 * ALOG(0.5)
      SHAPN  = EXP (EXPN)
      SHAPN1 = EXP (EXPN1)
      GO TO 1320
C
 1315 SHAPN  = 1.
      SHAPN1 = 1.
C
 1320 TRMNUM = 0.5 * (SHAPN*TRANS +
     *     SHAPN1*TRNEXT) * (WVNEXT-WAVLEN)
      TRMDEN     = 0.5 * (SHAPN*SHAPN1) * (WVNEXT-WAVLEN)
      SUMNUM     = SUMNUM +TRMNUM
      SUMDEN     = SUMDEN + TRMDEN
 1350 CONTINUE
C
      TEFF = SUMNUM/SUMDEN
      WRITE(2)  ACENTR, TEFF
      GO TO 1000
C
C
C     Close the files
C     - - - - - -
C
 5000 CLOSE (UNIT=2, DISP='KEEP')
      CLOSE (UNIT=3, DISP='DELETE')
      STOP
      END
```

NASA
National Aeronautics and
Space Administration

Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-100710		

4. Title and Subtitle	5. Report Date
Atmospheric Transmission Coefficients for Laser Pulses with Spectral Widths of a Few Tenths of a Nanometer, Over the Wavelength Region From 800 to 860 Nanometers	July 1988
	6. Performing Organization Code
	723

7. Author(s)	8. Performing Organization Report No.
H. G. Safren	88B0265
	10. Work Unit No.

9. Performing Organization Name and Address	
Goddard Space Flight Center Greenbelt, Maryland 20771	11. Contract or Grant No.
	13. Type of Report and Period Covered

12. Sponsoring Agency Name and Address	
National Aeronautics and Space Administration Washington, D.C. 20546-0001	Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Effective atmospheric transmission spectra were calculated from 800 to 860 nanometers, for laser sources with spectral widths of a few tenths of a nanometer. In this spectral region, the atmospheric absorption lines (water lines) have linewidths of a few hundredths of a nanometer, so that the transmission coefficient for a relatively wide laser pulse must be computed by taking a weighted average over the pulse spectral width. Laser spectral widths of several tenths of a nanometer are shown to reduce the effective absorption by water lines to as little as 10 or 20 percent, even when the laser is centered on a line or overlaps several lines. Thus, the effect of absorption by atmospheric water lines may be greatly reduced for laser communication systems using laser diode array transmitters, for which the pulse spectral width may be a few tenths of a nanometer.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Laser Communication Atmospheric Absorption	Unclassified - Unlimited Subject Category 17

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified		