Using the Navy Atmospheric Vertical Surface Layer Model (NAVSLaM) Version 2.0 MATLAB Code

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1. Introduction

The Navy Atmospheric Vertical Surface Layer Model (NAVSLaM) computes near-surface vertical profiles of parameters related to electromagnetic and electro-optical (EM/EO) propagation (refractivity or modified refractivity profiles, the evaporation duct height and the refractive index structure parameter profile) and profiles of thermodynamic meteorological quantities (temperature, humidity and pressure), as well as surface layer scaling parameters related to the air-sea fluxes of momentum, sensible heat and latent heat. NAVSLaM is only valid over the ocean and other large bodies of water. For over-land applications, use the associated NAVSLaM Two-Level model (NAVSLaM-2Lev). NAVSLaM requires as input standard near-surface meteorological parameters (wind speed, air temperature, humidity and pressure) defined at a single level, and the sea surface temperature. The primary use of NAVSLaM is to provide high-fidelity near-surface refractivity and optical turbulence (C_n^2) profile information needed as the environmental input to run propagation models. NAVSLaM Version 2.0 can compute EM/EO propagation-related parameters for both radio frequencies (1 Hz to 100 GHz) and optical wavelengths (0.3 to 14 microns), and has slightly different input and output parameters and requirements for these two different cases. This model version has been optimized to run very quickly with vector inputs and a MATLAB function is provided to run NAVSLaM with two-dimensional array inputs. These notes describe how to properly use the MATLAB code for NAVSLaM Version 2.0.

2. Executing NAVSLaM

The NAVSLaM Version 2.0 model function is executed by the following call from within a MATLAB code:

```
[ustar,tstar,qstar,l,edh,mmin,zprof,u,t,q,p,m,ctsq,cqsq,ctq,cnsq] = ...
      NAVSLaM_20_191008(lambda,ws,tair,tsea,h,hflag,pr,s,lat,az, ...
      zu,zt,zh,zp,zinc,zmax);
```

where

```
(lambda,ws,tair,tsea,h,hflag,pr,s,lat,az,zu,zt,zh,zp,zinc,zmax)
```

are the input parameters described in Section 3 and listed in Table 1, and

```
[ustar,tstar,qstar,l,edh,mmin,zprof,u,t,q,p,m,ctsq,cqsq,ctq,cnsq]
```

are the output parameters described in Section 5 and listed in Table 2.

3. Input Data

The input data parameters required by the NAVSLaM model are listed in Table 1, along with their required units and their valid bounds. All model input parameter values are checked to ensure that they fall within the valid bounds before executing the model. NAVSLaM can be run with in situ-measured, climatological or numerical weather prediction (NWP) model-predicted data as inputs. When measured meteorological data are being input to NAVSLaM, the data should have been averaged over an interval of at least 5 minutes, with 10 to 30 minutes being preferable. The measurement or valid forecast heights for the input atmospheric parameters should be between 0.5 and 50 m above the ocean surface, although heights between 2 m and 25 m are preferable, with the exception that forecasted surface pressure data (z = 0 m) can be used as input.

The input wind speed, air temperature, sea temperature and humidity values have a very strong impact on the NAVSLaM solutions, therefore if any of these parameters, or their associated valid heights, are outside the valid bounds shown in Table 1, then all NAVSLaM output parameters are set to −99 and the model does not execute for that specific case.

The input pressure, pressure height, salinity, latitude and azimuth of propagation have a secondary impact on the NAVSLaM solutions, and acceptable accuracy can be achieved when using reasonable default values. Therefore, if any of these parameters are out of bounds, NAVSLaM sets the parameter to a default value (pressure of 1013 hPa, pressure height of 0 m, salinity of 35 PSU, latitude of 40 degrees, azimuth of propagation of 45 degrees) and model execution continues. If data for any of these parameters is unavailable, then reasonable 'ballpark' or climatological values can be used, or the input values can be set to any out-of-bounds value (i.e. −99), and the model will automatically proceed with execution using the default values.

NAVSLaM can be run separately for either radio frequency (1 Hz to 100 GHz) or optical wavelength cases (0.3 to 14 microns), but not both in a single call to the NAVSLaM_20 function. For radio frequency runs (see Section 6), the *lambda* input parameter is always set to a value of 0 and can be either a scalar or array input. For optical wavelength runs (see Section 7), the *lambda* input parameter can have a value between 0.3 and 14 microns, and can be either a scalar input with a single wavelength to be used for every case in the input arrays, or a vector input with different wavelength values defined for each case.

NAVSLaM accepts as the humidity input parameter either relative humidity or specific humidity. All of the input humidity parameters must be of the same type for a single model run. The input humidity parameter type is identified by the input *hflag* humidity type indicator. If all of the input humidity parameters are relative humidity, then *hflag* is set to a scalar value of 1, and if all the input humidity parameters are specific humidity, then *hflag* is set to a scalar value of 2.

All NAVSLaM input parameters, with the exception of *hflag*, *zinc* and *zmax* which are always scalars, can be either scalars (i.e. single values) of shape (1,1), one-dimensional row vectors of shape (1,n) or one dimensional column vectors of shape (n,1), where n is the total number of elements in the input arrays. Certain input parameters (*lambda*, *s*, *lat*, *az*, *zu*, *zt*, *zh*, *zp*) can be scalars, even when the primary meteorological inputs (*u*, *tair*, *tsea*, *h*, *pr*) are vectors. For best performance the inputs should be column vectors. All input arrays must have the same shape, otherwise NAVSLaM does not execute and it returns an error message and values of −99 for all output parameters. The input wavelength (*lambda*), salinity (*s*), latitude (*lat*), azimuth of propagation (*az*) and the valid heights for wind speed (*zu*), temperature (*zt*), humidity (*zq*) and pressure (*zp*) can either be an array of values with dimensions corresponding to the primary meteorological parameter input arrays, or a scalar value if the user wishes to use the same value for all input cases.

When array inputs are being used and it is desired to use the same value for all cases for a certain input parameter, such as assuming a value of 70% for the relative humidity in all input cases, then the following type of MATLAB statement should be used to define the input parameter before calling the NAVSLaM function:

```
h = 70*ones(size(u)) ;
```

where *u* is the input wind speed array (although any input array can be used).

4. Defining the Output Vertical Profile Heights

The user has two options for defining the heights at which the output vertical profile array elements are computed:

a) Option 1 – Define a height array with constant vertical spacing: The user may allow the NAVSLaM model to compute a height array with constant increments between height levels by setting the *zinc* and *zmax* input parameters to appropriate scalar values. This approach is recommended for radio-frequency model runs, but can also be used for optical wavelength runs. The heights at which the output vertical profile elements are defined are determined by the *zinc* and *zmax* input parameters. The *zinc* parameter defines the increment between height levels. The *zmax* parameter defines the top height of the output vertical profile arrays. A value of between 50 and 100 m is recommended for *zmax*, and a value of greater than 100 is not allowed. The number of height levels (*nprof*) in the output vertical profile arrays is therefore *nprof* = *zmax*/*zinc* + 1, where the first element is always valid at the surface (*z* = 0 m). For example, with input values of *zinc* = 0.1 m and *zmax* = 100 m, the output vertical profile arrays have 1001 vertical levels, as follows:

   zprof = [0, 0.1, 0.2, 0.3, 0.4, 0.5,. . . 99.5, 99.6, 99.7, 99.8, 99.9, 100].

   There are special considerations for the *zinc* and *zmax* parameters when running NAVSLaM for radio frequency or optical wavelength cases, as described in Sections 6 and 7 below.

b) Option 2 – Input a pre-defined height array with constant or variable vertical spacing: The user may directly input a pre-defined height array into NAVSLaM. When this approach is used, the height array is input as the *zinc* parameter, and the *zmax* input parameter is not used. This approach is more appropriate for optical wavelength model applications and is not recommended for radio-frequency applications, since it may not have sufficient vertical resolution to characterize the evaporation duct. The first element of the height array must be defined at the surface (= 0), and the remaining height levels must increase monotonically. An example input height arrays is:

```
zinc = [0 1 2 5 10 20 50 100] ;
```

An example of MATLAB code to pre-define an input height array with logarithmic spacing is:

```
zinc(1) = 0 ;
zinc(2:12) = (10.^[0:0.1:1])/10 ;
zinc(13:32) = 10.^[0.1:0.1:2] ;
```

or to define a logarithmic height array with higher resolution above 1 m:

```
zinc(1) = 0 ;
zinc(2:12) = (10.^[0:0.1:1])/10 ;
zinc(13:52) = 10.^[0.05:0.05:2] ;
```

5. Output Data

The NAVSLaM output data parameters and their units are described in Table 2. The dimensions of the output arrays are dependent upon the dimensions of the input arrays, as shown in Table 3.

In certain cases the output data parameters have been set to pre-determined negative values to indicate the input data are bad, or there is a problem with the NAVSLaM model run, or when parameters are undefined, as follows:

1) If any input parameter other than pressure (*pr*), pressure height (*zp*), salinity (*s*), latitude (*lat*) or azimuth of propagation (*az*) is outside of the valid bounds indicated in Table 1, or if the input array dimensions do not match, then all output parameters are set to −99.

2) If the iterative solution for the surface layer scaling parameters does not converge, all the output parameters are set to −98. This should not occur.

3) If the air temperature or specific humidity have unrealistic values (T_{air} > 50°C or $q_{air} \leq 0$ kg/kg or $q_{air} > q_{sat}$), all the output vertical profile values (*m*, *t*, *q*, and *p*) for the cases and levels with unrealistic air temperature or specific humidity values are set to −97. If either the air temperature or specific humidity profiles have unrealistic values at any height level between the surface and the evaporation duct height, then *edh* and *mmin* are set to −97.

4) For radio frequency cases, if the evaporation duct height is not defined (i.e. the minimum modified refractivity profile value occurs at the top height of the *zprof* array, as shown in Figure 1c), then the evaporation duct height (*edh*) and the minimum *m* value (*mmin*) are set to −96.

5) For optical wavelength cases (*lambda* > 0), the evaporation duct height (*edh*) and the minimum *m* value (*mmin*) are set to −99.

6) The surface value (z = 0 m) of the vertical refractive index structure parameter profile (*cnsq*) is undefined and is therefore set to NaN.

Note that very small and insignificant differences may be noted in the model output parameters between when a particular case is run individually with scalar inputs to the model, or when the case is run as one of many cases within an array of input data to the model. This is due to the fact that when the model is run with array inputs, the iteration process to determine the surface layer scaling parameters is continued until all cases within the input data arrays have reached the convergence criteria, potentially resulting in more iterations occurring as compared to when only a single case is run. This can result in very slightly different model output values.

6. Radio Frequency Cases

For radio frequency cases, NAVSLaM focuses on predicting the vertical modified refractivity profile, which takes into account the curvature of the earth and is useful for identifying trapping layers, and the associated evaporation duct height, which is the most important single parameter for quantifying near-surface radio frequency propagation conditions. NAVSLaM also predicts the vertical refractive index structure parameter (C_n^2) profile, which can become important at higher radio frequencies. The output temperature, humidity and pressure profiles can also be used to compute the gaseous attenuation of radio frequency signals.

When running NAVSLaM for radio frequency cases (1 Hz to 100 GHz), the *lambda* input parameter must always be set to a value of 0, and can be either a scalar or array input. Radio frequency and optical wavelength cases cannot be combined in the same NAVSLaM call.

For radio frequency cases, the output m parameter represents the vertical modified refractivity profile, defined as:

$$m(z) = (n-1)\times 10^6 + 10^6 \frac{z}{R_e} = k_1 \frac{P(z)}{T(z)} + k_2 \frac{e(z)}{T(z)} + k_3 \frac{e(z)}{T^2(z)} + 10^6 \frac{z}{R_e}.$$

where n is the index of refraction, T is the air temperature, P is the total atmospheric pressure, e is the water vapor pressure, z is the height above the surface, R_e is the radius of curvature of the Earth and k_1, k_2 and k_3 are empirical constants.

The evaporation duct height, *edh*, is defined as the height at which the local minima in the vertical modified refractivity (m) profile nearest to the surface occurs (which is the *mmin* output parameter), as seen in Figure 1, panels a and b. When there is no evaporation duct present (i.e. the minimum value of m is at the surface, z = 0 m, as shown in Figure 1d), *edh* has a value of 0 m. When NAVSLaM cannot define the evaporation duct height within the model height domain defined by *zmax* (i.e. the minimum value of m occurs at *zmax*, and therefore the local minima in m has not been reached within the model height domain, as shown in Figure 1c), then *edh* and *mmin* are set equal to −96.

In order to properly characterize the evaporation duct for propagation modeling purposes, it is recommended to use a value between 50 and 100 m for *zmax*, and a value of 0.1 m for *zinc*. Values for *zmax* greater than 100 m are not allowed by NAVSLaM, and are set to a default value of 100 m.

7. Optical Wavelength Cases

For optical wavelength cases, NAVSLaM focuses on predicting the vertical refractive index structure parameter (C_n^2) profile, which is very important in determining the degradation of laser beam and optical and infrared imaging quality due to optical turbulence, and also the vertical refractivity profile for describing refractive effects. There is no analogous feature to the radio frequency evaporation duct for optical wavelength propagation.

When running NAVSLaM for optical wavelength cases, the *lambda* input parameter must have values within the following windows: 0.3-2.5 microns, 2.8-4.2 microns, 4.4-5.2 microns, and 7.5-14 microns. *lambda* can be either a scalar value if the user desires to use the same wavelength for all input cases, or an array of input values if the input cases have different wavelengths.

Since there is no need to define the evaporation duct height for optical wavelength cases, the user has more freedom to set *zmax* and *zinc* to any values desired to define the height levels of interest, or to use a pre-defined input height array. For example, if the user is interested in computing values of *cnsq* at a single height level, such as 10 m, then the user should set both *zmax* and *zinc* to the same value of 10 m. In such a case the output profile arrays will have two elements, with the first being the surface value (z = 0 m) and the second being the value at height *zmax*. Note that the surface value (z = 0 m) of *cnsq* is undefined and is therefore always set to NaN.

For optical wavelength cases, the output *m* parameter represents the vertical refractivity profile, defined as:

$$m(z) = (n-1)\times 10^6 = c_1(\lambda)\frac{P(z)}{T(z)} + c_2(\lambda)\frac{e(z)}{T(z)}.$$

where n is the index of refraction, T is the air temperature, P is the total atmospheric pressure, e is the water vapor pressure, z is the height above the surface and c_1 and c_2 are empirical functions of the wavelength, λ.

For optical wavelengths there is no analogous evaporation duct-type feature present in the refractivity profile, and therefore the output *edh* and *mmin* parameters are set to NaN for all optical wavelength cases. Note also that for optical cases the azimuth of propagation (*az*) input parameter is not used.

8. Sample Code to Run NAVSLaM with Test Cases

A sample MATLAB code, Test_NAVSLaM_20_191008.m, is provided to run the MATLAB NAVSLaM_20_191008.m code with input data from four separate test case data files. The four test case data files cover four different types of runs, as follows:

1) NAVSLaM_20_test_input_rf_rh.txt – Radio frequency cases with relative humidity input
2) NAVSLaM_20_test_input_rf_q.txt – Radio frequency cases with specific humidity input
3) NAVSLaM_20_test_input_op_rh.txt – Optical wavelength cases with relative humidity input
4) NAVSLaM_20_test_input_op_q.txt – Optical wavelength cases with specific humidity input

The test program reads these data files, runs the NAVSLaM_20_191008 code with the input data arrays, writes a sample of output data to a file, and plots output vertical profiles for a single test case. The output data file names are similar to the input data files, with 'output' replacing 'input' in the file name. The format of the test case output data files is as follows:

1) Column 1 – Test case number
2) Column 2 – Evaporation duct height (*edh*) in m
3) Column 3 – Minimum *m* value
4) Column 4 – Wind speed surface layer scaling parameter, or 'friction velocity' (*ustar*) in m/s
5) Column 5 – Air temperature surface layer scaling parameter (*tstar*) in °C
6) Column 6 – Specific humidity surface layer scaling parameter (*qstar*) in kg/kg
7) Column 7 – Obukhov length scale (*l*) in m
8) Column 8 – Wind speed (*u*) at 5 m in m/s
9) Column 9 – Air temperature (*t*) at 5 m in °C
10) Column 10 – Specific humidity (*g*) at 5 m in g/kg
11) Column 11 – Pressure (*p*) at 5 m in hPa
12) Column 12 – Modified refractivity (*m*) at 5 m
13) Column 13 – Refractive index structure parameter (*cnsq*) at height = 5 m in $m^{-2/3}$

A sample figure created by the Test_NAVSLaM_20_191008 function is shown in Figure 2 for Case #2 from the radio frequency with specific humidity input test cases. The test program also provides an example of running the NAVSLaM model with a pre-defined height array with logarithmic vertical spacing, and plots a single test case, as shown by the examples in Figure 3.

9. Running NAVSLaM with 2-Dimensional Input Data Arrays

NAVSLaM can be run with 2-dimensional input arrays, such as with meteorological data defined on a latitude-longitude grid, using the NAVSLaM_20_2D function. This function performs the following steps: 1) Takes the 2-dimensional input arrays and converts them to 1-dimensional column vectors, 2) Inputs these 1-dimensional vectors into the NAVSLaM_20 function, 3) Converts the 1-dimensional output arrays from NAVSLaM_20 back into 2-dimensional arrays corresponding to the dimension sizes of the original 2-D input arrays. NAVSLaM_20_2D is executed using a MATLAB function call statement analogous to that presented in Section 2.0, with 'NAVSLaM_20_2D' replacing 'NAVSLaM_20'. The input data arrays scan have the shape (*nlat*,*nlon*) or (*nlon*,*nlat*) where *nlat* is the number of latitude (or other y coordinate) points in the grid, and *nlon* is the number of longitude (or other x coordinate) grid points. The input and output array dimensions for function 'NAVSLaM_20_2D' are shown in Table 4.

Table 4. NAVSLaM_20_2D Two-Dimensional Input and Output Array Dimensions

Input Type	Input Dimensions	Non-Profile Output Dimensions (*edh, mmin, ustar, tstar, qstar, l*)	Height Profile Output Dimensions (*zprof*)	Vertical Profile Output Dimensions (*u, t, q, p, m, ctsq, cqsq, ctq, cnsq*)
2D Array	(*nlat*,*nlon*)	(*nlat*,*nlon*)	(*nprof*,1)	(*nlat*,*nlon*,*nprof*)
2D Array	(*nlon*,*nlat*)	(*nlon*,*nlat*)	(*nprof*,1)	(*nlon*,*nlat*,*nprof*)

Regardless if whether the input 2-dimensional arrays have the form (*nlat*,*nlon*) or (*nlon*,*nlat*), the output 2-dimensional arrays (*edh*, *mmin*, *ustar*, *tstar*, *qstar*, *l*) can be contour plotted using a MATLAB statement of the form:

```
contourf(lon,lat,edh(:,:))
```

and a single height level from the output 3-dimensional vertical profile arrays (*u*, *t*, *q*, *p*, *m*, *ctsq*, *cqsq*, *ctq*, *cnsq*) can be contour plotted using a MATLAB statement of the form:

```
contourf(lon,lat,cnsq(:,:,nht))
```

where *lat* is the one-dimensional array of latitude (or other y coordinate) values, *lon* is the one-dimensional array of longitude (or other x coordinate) values and *nht* is the array pointer for the height of interest to be plotted.

10. Reporting Issues and Problems

Users encountering any problems or unusual issues in using the MATLAB code for NAVSLaM Version 2.0 are encouraged to contact Paul Frederickson by phone (831-521-8670), or email (pafreder@nps.edu) with details of the issues encountered, including especially the input data being used and any error messages or erroneous results being returned by the NAVSLaM_20 or NAVSLaM_20_2D functions. Suggestions for improving the model are also very welcome.

11. Obtaining and Sharing the MATLAB Code

This NAVSLaM model version has not yet been accepted into the Oceanic and Atmospheric Master Library (OAML) as a U.S. Navy standard, and should therefore be considered a 'research and development' version. Distribution of the model code and documentation is restricted to U.S. Government agencies. For this reason, please do not share the NAVSLaM v2.0 MATLAB code or documentation with others, but rather refer researchers and colleagues interested in obtaining NAVSLaM to me. This way I can keep track of who has the model code, what version they are using, and what purpose they are using the model for, which is helpful to me as a developer. Thank you!

Table 1. **NAVSLaM input parameters.**

Name	Description	Scalar or Array	Units	Valid Bounds
lambda	Radio frequency indicator (always = 0) or wavelength for optical cases	Either	microns or none if = 0	0 or $0.3 \le lambda \le 14$ (See note a)
ws	Wind speed at height *zu* above the surface	Array	m/s	$0 \le u \le 30$
tair	Air temperature at height *zt* above the surface	Array	°C	$-40 \le tair \le 50$
tsea	Sea surface temperature	Array	°C	$-2.6 \le tsea \le 36$
h	Humidity parameter, either relative humidity or specific humidity, as indicated by hflag, at height *zq* above the surface	Array	% for *RH;* kg/kg for *q*	$10 \le RH \le 100$ $0 < q \le 0.1$
hflag	Humidity (*h*) input parameter indicator: 1 = relative humidity; 2 = specific humidity	Scalar	N/A	1 or 2
pr	Atmospheric pressure at height *zp* above the surface, or at the surface if *zp* = 0 m	Array	hPa	$920 \le pr \le 1060$ (See note b)
s	Ocean surface salinity	Either	PSU	$0 \le s < 60$ (See note c)
zu	Height above the surface at which *u* is valid (measured or forecasted)	Either	m	$0.5 \le zu \le 50$
zt	Height above the surface at which *tair* is valid (measured or forecasted)	Either	m	$0.5 \le zt \le 50$
zh	Height above the surface at which *h* is valid (measured or forecasted)	Either	m	$0.5 \le zq \le 50$
zp	Height at or above the surface at which *pr* is valid (measured or forecasted)	Either	m	$0 \le zp \le 50$ (See note d)
lat	Latitude	Either	degrees	$-90 \le lat \le 90$ (See note e)
az	Azimuth of propagation (not used for optical wavelength cases)	Either	degrees	$0 \le az \le 360$ (See note f)
zinc	If a scalar value, *zinc* defines the height interval between levels of the output *t*, *q*, *p*, *m* and *cnsq* vertical profile arrays; or *zinc* can be a pre-defined input height array.	Scalar or Array	m	$0 < zinc \le zmax$ (0.1 m is recommended for radio frequency cases)
zmax	Maximum height for the output *t*, *q*, *p*, *m* and *cnsq* vertical profile arrays (not used if *zinc* is a pre-defined height array).	Scalar	m	$0 < zmax \le 100$

Table 1 Notes:

a. For radio frequencies cases, the *lambda* input value is always set to a scalar value of 0. For optical wavelength cases, *lambda* can be either a scalar value when it is desired to use the same wavelength for all cases, or an array of values when the wavelength changes between different cases. For optical wavelength cases, *lambda* must have a value within the following windows: 0.3-2.5 microns, 2.8-4.2 microns, 4.4-5.2 microns, and 7.5-14 microns. Radio frequency and optical wavelength input cases cannot be combined in a single call to NAVSLaM.

b. Pressure values outside the indicated valid bounds are set to a default value of 1013.25 hPa.

c. Salinity values outside the indicated valid bounds are set to a default value of 35 PSU.

d. Pressure height values outside the indicated valid bounds are set to a default value of 0 m.

e. Latitude values outside the indicated valid bounds are set to a default value of 40 degrees.

f. Azimuth values outside the indicated valid bounds are set to a default value of 45 degrees.

Table 2. NAVSLaM output parameters.

Name	Description	Units
ustar	Wind speed surface layer scaling parameter, $u_* \equiv \langle -w'u' \rangle^{1/2}$	m/s
tstar	Air temperature surface layer scaling parameter, $T_* \equiv -\langle w'T' \rangle / u_*$	°C
qstar	Specific humidity surface layer scaling parameter, $q_* \equiv -\langle w'q' \rangle / u_*$	kg/kg
l	Obukhov length scale, $L = \theta_v u_*^2 / (kg[T_*(1+\gamma q) + \gamma T q_*])$	m
edh	Evaporation duct height	m
mmin	Modified refractivity value at the evaporation duct height	None
zprof	Vertical height array, either defined by the input *zinc* and *zmax* values if these parameters are scalars, or identical to the pre-defined height array *zinc*, if *zinc* is an array. *zprof* defines the heights at which the output *t*, *q*, *p*, *m* and *cnsq* vertical profile array values are computed.	m
u	Vertical wind speed profile array with values corresponding to the heights defined by the *zprof* array	m/s
t	Vertical air temperature profile array with values corresponding to the heights defined by the *zprof* array	°C
q	Vertical specific humidity profile array with values corresponding to the heights defined by the *zprof* array	kg/kg
p	Vertical atmospheric pressure profile array with values corresponding to the heights defined by the *zprof* array	hPa
m	Vertical modified refractivity profile array for radio frequency cases (*lambda* = 0), or vertical refractivity profile array for optical wavelength cases (*lambda* > 0), with values corresponding to the heights defined by the *zprof* array	None
ctsq	Vertical temperature structure parameter (C_T^2) profile array with values corresponding to the heights defined by the *zprof* array	$K^2\ m^{-2/3}$
cqsq	Vertical humidity structure parameter (C_q^2) profile array with values corresponding to the heights defined by the *zprof* array	$m^{-2/3}$
ctq	Vertical temperature-humidity cross-structure parameter (C_{Tq}) profile array with values corresponding to the heights defined by the *zprof* array	$K\ m^{-2/3}$
cnsq	Vertical refractive index structure parameter (C_n^2) profile array with values corresponding to the heights defined by the *zprof* array	$m^{-2/3}$

Table 2 Notes:

a. All output parameters are set to −99 if any input parameter other than *pr*, *zp*, *s*, *lat* or *az* is outside of the valid bounds indicated in Table 1, or if the input array dimensions do not match.

b. All the output parameters are set to −98 if the iterative solution for the surface layer scaling parameters does not converge. This should not occur.

c. The vertical profile values (*m*, *t*, *q*, and *p*) for the cases and levels with unrealistic air temperature or specific humidity values (T_{air} > 50°C or $q_{air} \leq 0$ kg/kg or $q_{air} > q_{sat}$) are set to −97.

d. *edh* and *mmin* are set to −97 if either the air temperature or specific humidity profiles have unrealistic values (T_{air} > 50°C or $q_{air} \leq 0$ kg/kg or $q_{air} > q_{sat}$) at any height level between the surface and *edh*.

e. *edh* and *mmin* are set to −96 if the evaporation duct height is not defined (i.e. the minimum modified refractivity profile value occurs at the top height of the modified refractivity profile array).

f. *edh* and *mmin* are set to −99 for optical wavelength cases (*lambda* > 0).

g. The surface values (*z* = 0 m) of the *ctsq*, *cqsq*, *ctq* and *cnsq* profile arrays are undefined and are therefore always set to NaN.

Table 3. NAVSLaM Input and Output Dimensions

Input Type	Input Dimensions	Non-Profile Output Dimensions (*edh*, *mmin*, *ustar*, *tstar*, *qstar*, *l*)	Height Profile Output Dimensions (*zprof*)	Vertical Profile Output Dimensions (*t*, *q*, *p*, *m*, *cnsq*)
Scalar	(1,1)	(1,1)	(1,*nprof*)	(1,*nprof*)
Column vector	(*n*,1)	(*n*,1)	(1,*nprof*)	(*n*,*nprof*)
Row vector	(1,*n*)	(1,*n*)	(*nprof*,1)	(*nprof*,*n*)
n = number of elements in the input data arrays (i.e. the number of individual cases to be run)				
nprof = number of height levels in the vertical profile output arrays (*nprof* = *zmax*/*zinc* + 1)				

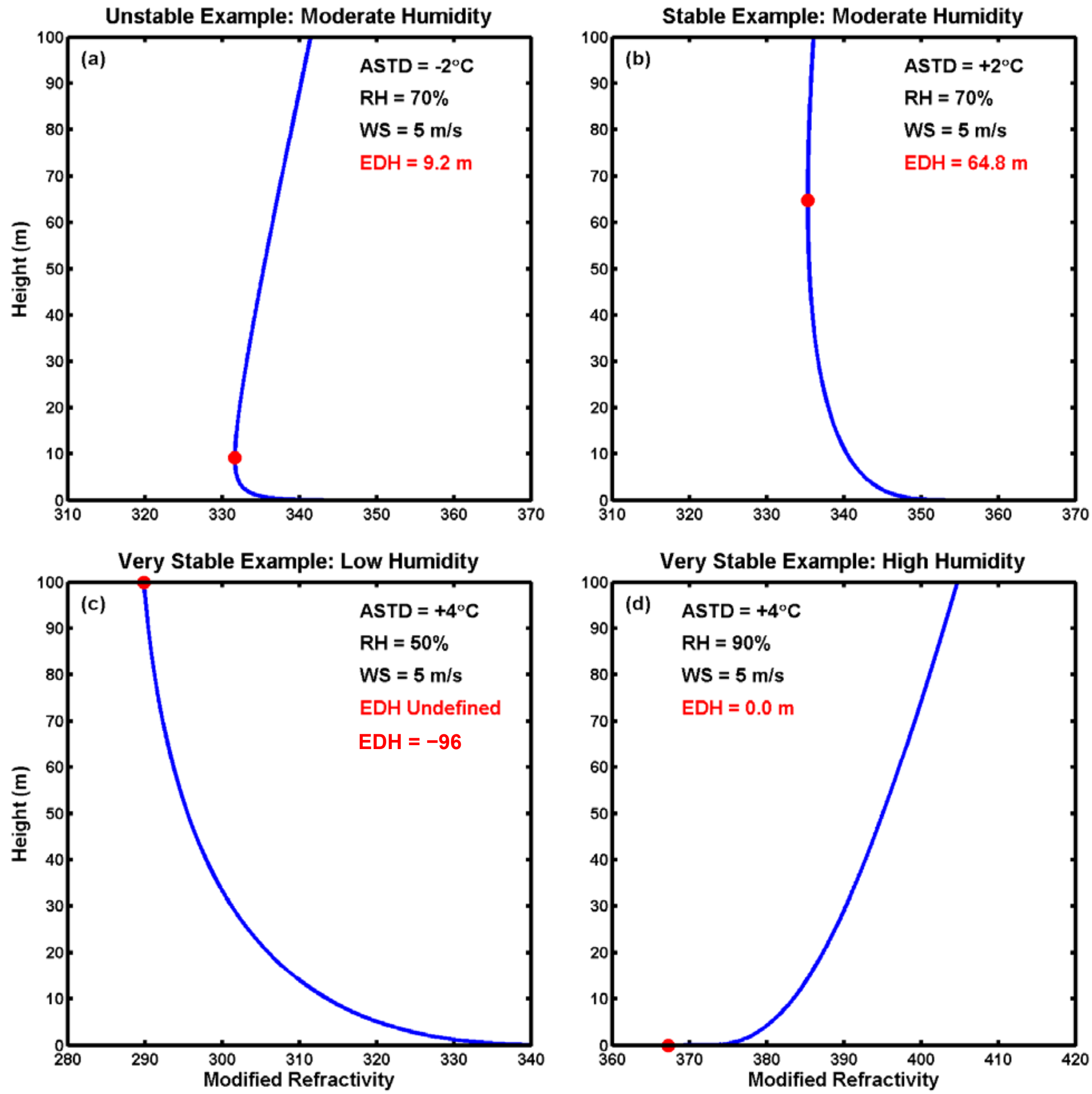

Figure 1. Plots of vertical modified refractivity (*m*) profiles computed by the NAVSLaM Version 2.0 model for four different types of environmental conditions: Panel a) Unstable conditions with an air-sea temperature difference of –2°C and relative humidity of 70%; b) Stable conditions with an air-sea temperature difference of +2°C and relative humidity of 70%; c) Very stable conditions with an air-sea temperature difference of +4°C and relative humidity of 50%. The evaporation duct height is undefined in this case and is set to –96; d) Very stable conditions with an air-sea temperature difference of +4°C and relative humidity of 90%. There is no evaporation duct present in this case and the evaporation duct height is set to 0 m, the height at which the minima in *m* occurs. In all cases the wind speed was 5 m/s, the sea surface temperature was 20°C and the surface pressure was 1010 hPa.

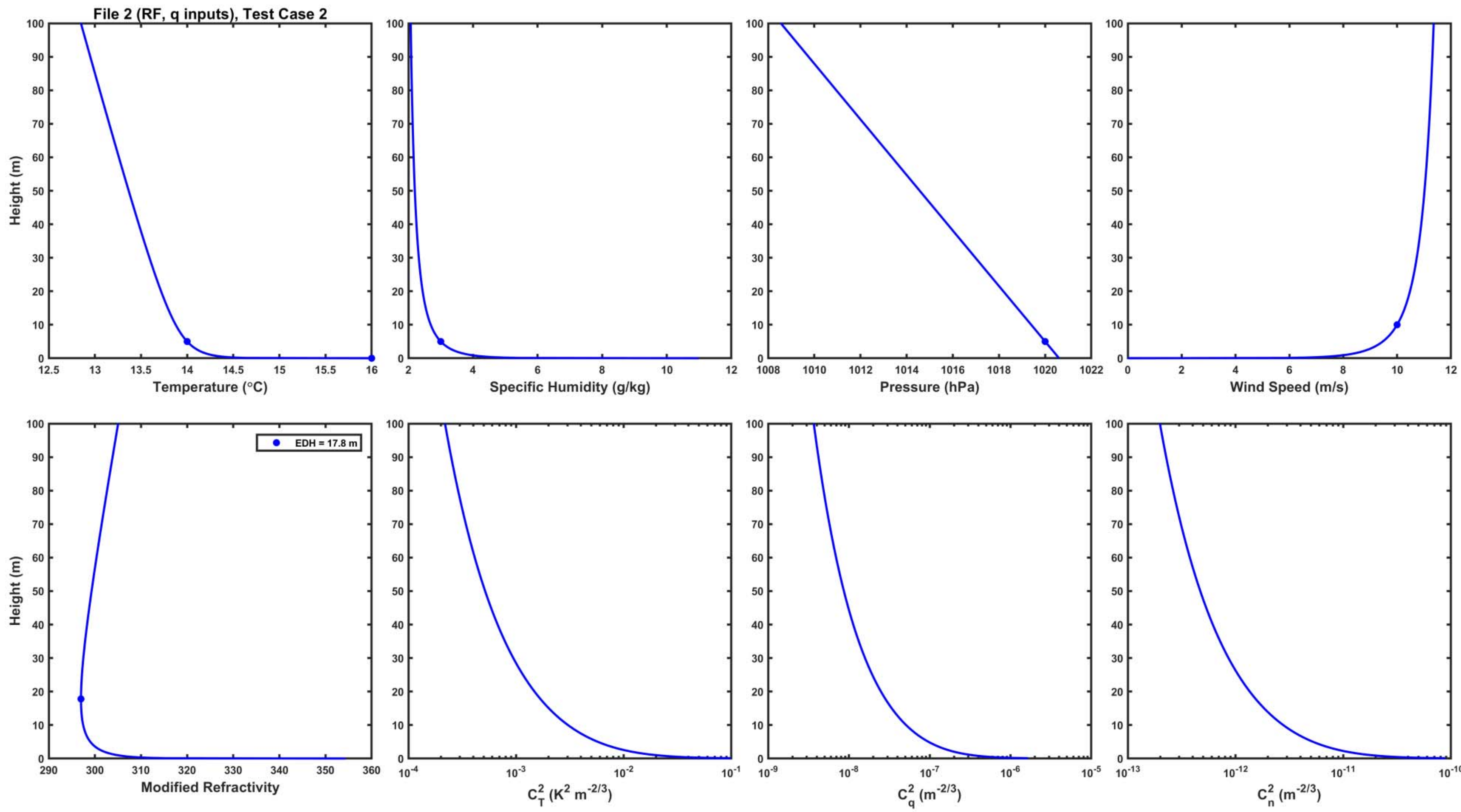

Figure 2. Sample figure created by the Test_NAVSLaM_20_191008 function for Case #2 from the radio frequency with specific humidity input test cases, showing vertical profiles of most NAVSLaM output parameters. The blue dots show the NAVSLaM input values, except for the modified refractivity plot in which the blue dot indicates the evaporation duct height.

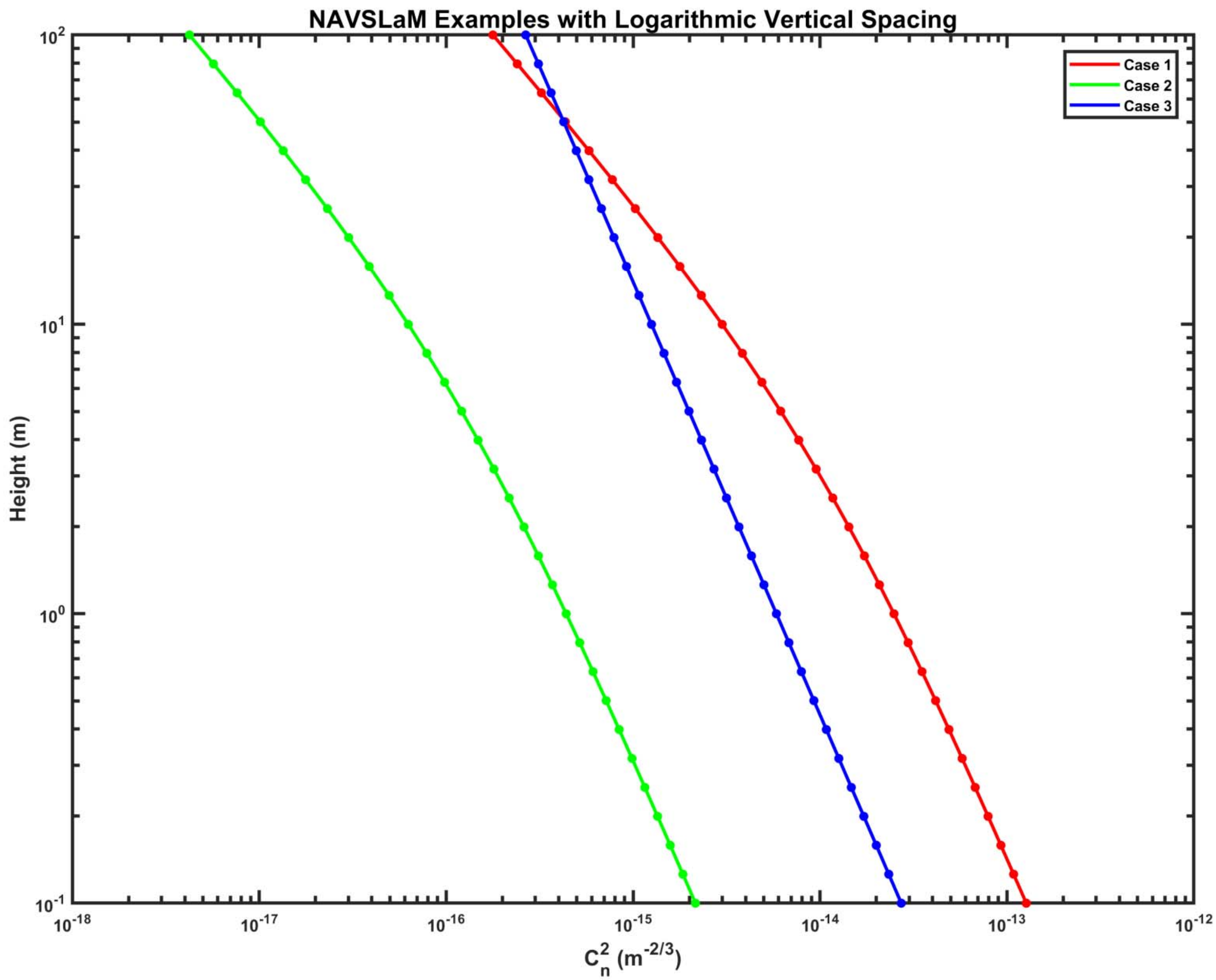

Figure 3. Plot created by the Test_NAVSLaM_20_191008 function, showing examples of vertical refractive index structure parameter (C_n^2) profiles with logarithmically-spaced height intervals.