

# 3D Atmospheric Modeling based on MODTRAN4

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**Abstract:** - All the factors of atmospheric environment that influence the transmission of infrared radiation were analyzed in detail in the paper. Taking horizontally varying atmospheric property into consideration, a 3D model of atmospheric transmission of infrared radiation is established based on MODTRAN4. Moreover, the methods of calculating the ratio of atmospheric transmission, path radiation and single scatter solar radiation are presented. This 3D model is running by using the spectral database generated by MODTRAN4. It can handle attenuation of infrared radiation through the 3D atmosphere when target is below 60km. Implementation details are also presented.

**Key-Words:** - Infrared Radiation, Model, MODTRAN4, Path Radiation, Ratio of Atmospheric Transmission, Simulation, Single Scatter Solar Radiation

## 1 Introduction

Nowadays the widely used atmospheric radiative transfer models are two dimensional models such as LOWTRAN[6], MODTRAN4[1] and FASCODE[7]. For example, MODTRAN4 [1][2] is the U.S. Air Force (USAF) standard moderate spectral resolution radiative transport model for wavelengths extending from the thermal Infrared (IR) through the visible and into the ultraviolet (0.2 to 10,000.0  $\mu\text{m}$ ). Within MODTRAN4, there can be vertical variations within the profile, but there can be no change in the horizontal structure of the atmosphere[10]. This treatment of the atmosphere as homogeneous slabs is actually a limitation of MODTRAN. To improve the reliability and fidelity of infrared imaging simulation system, the atmospheric radiative transfer model should take both the vertical and horizontal structure of the atmosphere. The center for imaging science Rochester institute of technology proposed the improvement to the DIRSIG model to incorporate three dimensional atmospheric variability into DIRSIG[3]. The 3D atmospheric radiative transfer model (3DARTM) is a module based on MODTRAN4 for calculating atmospheric transmission, thermal emission, and single scattering solar radiance along sensor-to-target lines-of-sight (LOS) within a three dimensionally varying atmosphere[11][12][13]. The 3D model works by scaling and interpolating an atmospheric grid of spectral data to local conditions, and incorporating this data in radiative transport LOS integrations. It can be run using either a default or customized MODTRAN4-generated spectral database.

Taking horizontally varying atmospheric property into consideration, a 3D model of atmospheric transmission of infrared radiation is established based on MODTRAN4. The working mechanism of this model is inserting an atmosphere grid of a scaled spectral data in to local atmospheric conditions, and using these data to calculate the ratio of atmospheric transmission, path radiation and single scatter solar radiation respectively. A default or customized MODTRAN4 generated spectral data base was used here. The interfaces are shown in figure 1.

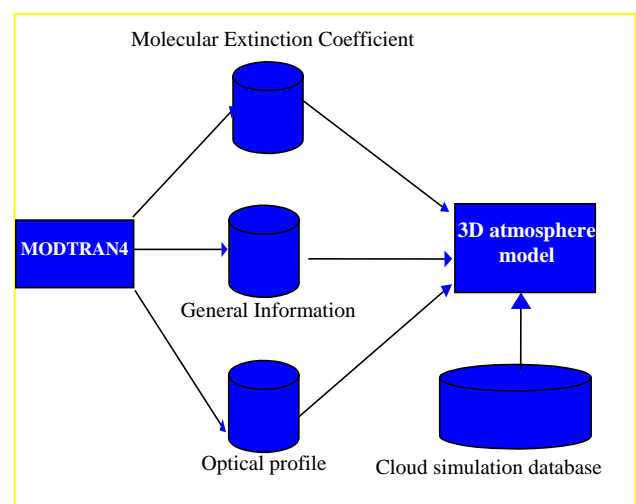


Fig. 1 the interfaces of the 3D atmospheric radiative transfer model

## 2 Modeling and Analysis

The atmosphere is composed of gases and suspended particles at various temperature and pressures as a function of altitude and azimuth[8]. So the atmosphere should be vertically divided into  $N$  layers. Because the atmosphere varies horizontally, it needs to be divided into  $M$  molecule extinction intervals vertically [3]. In addition, MODTRAN4 has been modified to output a set of files for input into 3DARTM. While these MODTRAN4-generated files define the optical properties of a baseline atmosphere, 3DARTM also requires the atmospheric conditions for the current local environment. Once the atmospheric properties are defined, the propagation and emission of radiation along a given line-of-sight (LOS) can be calculated[11][12][13]. A LOS is divided into sub-paths depending of the intersection of the LOS with the top of the atmosphere. Each sub-path is further divided into segments. Each segment contains the local atmospheric conditions and pre-computed interpolation coefficients for the optical properties within that segment. Once the LOS is segmented into sub-paths and segments, propagation proceeds by calculating the local contribution of the each segment to the total emission and scattered solar radiation beginning with the end segment and proceeding to the segment ending at the observer location. Correct application of Beer's Law requires that the propagation calculation occurs spectrally—that is at very fine wavelength intervals. An approximate solution is obtained by using a "correlated-k" band model. The band model accumulates spectral values for the transmission, emission, and solar scattering at sub-band resolution and then computes the final in-band LOS values as weighted averages.

### 2.1 Optical Properties of a Baseline Atmosphere

MODTRAN4 has been modified to output a set of files for setting the optical properties of a baseline atmosphere. These files contain key atmospheric profile information, including:

- Spectral resolution and band pass.
- k-distribution weighting factors.
- Baseline pressure dependent profiles for H<sub>2</sub>O, CO<sub>2</sub> and O<sub>3</sub> in g/m<sup>3</sup>.
- Profile scale factors used in each MODTRAN calculation.
- Scattering cross-sections, extinction cross-sections, and scattering asymmetry factors for aerosols, clouds and rain.
- Molecular scattering cross-sections.

- Molecular extinction cross-section data.
- 3DARTM also requires the atmospheric conditions for the current local environment. These properties are defined over a 3D bounded space and include local pressure, temperature and density.
- Pressure in atmospheres [ATM].
  - Temperature in Kelvin [K].
  - Aerosol extinction is reciprocal kilometers at 550nm [KM<sup>-1</sup>].
  - Cloud particle density in grams per meter cubed [gm/m<sup>3</sup>].
  - Rain Rate in millimeter per hour raised to the 0.63 power [(mm/hr)<sup>0.63</sup>].
  - Gaseous H<sub>2</sub>O density in grams per meter cubed [gm/m<sup>3</sup>].
  - Gaseous CO<sub>2</sub> density in grams per meter cubed [gm/m<sup>3</sup>].
  - Gaseous O<sub>3</sub> density in grams per meter cubed [gm/m<sup>3</sup>].

The units for aerosol and rain rate may seem unusual or strange. The rain rate is raised to the 0.63 power because the rain extinction in MODTRAN4 is modeled as varying linear, and 3DARTM will execute more rapidly if the data is stored this way.

### 2.2 Line-of-sight

According to whether the line-of-sight between sensor and target intersect with the boundary of the atmosphere, and the position of the intersection, LOS is divided into sub-paths. Each sub-path is further divided into a sequence of segments. The boundary of the atmosphere should be higher than the height of the clouds and lower than the top of the atmosphere. The default value for the boundary of the atmosphere is 20km.

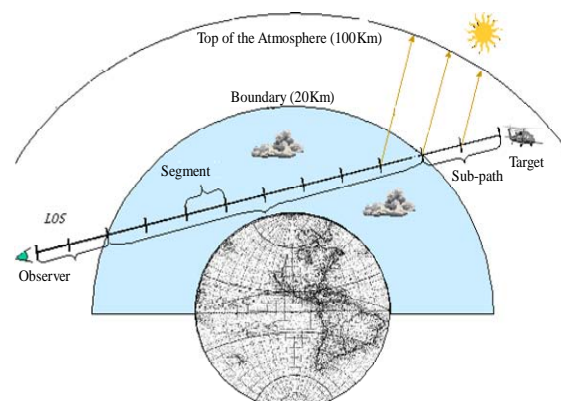


Fig. 2 the setting of LOS

As shown in figure 2, the LOS intersects with the boundary of the atmosphere twice, so the LOS could be divided as upper sub-path and lower sub-path. If the LOS does not intersect with the boundary, then there is only one sub-path.

### 2.3 Local Atmospheric and Optical Properties of Segment

Each segment contains front-point, center and end-point. The atmospheric properties at the three points can be calculated by interpolation. Then, the local average atmospheric properties of segment should be set to the atmospheric properties of center. Since cloud and rain distributions have considerable structure[9], their segment average densities are defined from three-point averages.

$$Avg_{cloud} = (Beg_{cloud} + 2 * Cen_{cloud} + End_{cloud}) / 4 \quad (1)$$

where  $Avg_{cloud}$ ,  $Beg_{cloud}$ ,  $Cen_{cloud}$ ,  $End_{cloud}$  refer to cloud particle density of segment, front-point, center and end-point respectively.

$$Avg_{rain} = (Beg_{rain} + 2 * Cen_{rain} + End_{rain}) / 4 \quad (2)$$

where  $Avg_{rain}$ ,  $Beg_{rain}$ ,  $Cen_{rain}$ ,  $End_{rain}$  refer to Rain Rate of segment, front-point, center and end-point respectively. The units for rain rate is millimeter per hour raised to the 0.63 power. The rain rate is raised to the 0.63 power because the rain extinction in MODTRAN4 is modeled as varying linear with this term, and 3DARTM will execute more rapidly if the data is stored this way.

Finally, according to the atmospheric properties of center, the parameters of molecular extinction interpolation table, including pressure interpolation fraction, molecular atmospheres, H<sub>2</sub>O interpolation fraction, CO<sub>2</sub> interpolation fraction and O<sub>3</sub> interpolation fraction, can be calculated for each segment. And the parameters of molecular extinction interpolation table can be also calculated for solar path of each segment.

### 2.4 Optical Properties of Solar Path

For each segment, a line is made from the front end of the segment to the current position of the sun at the geocentric coordinates. The line intersects the top of atmosphere at a point. The range from the point to the front end of the segment is defined as the solar path for the segment. Firstly, the least range from the solar path to the center of the earth is compared with the radius of the earth. If the least range from the solar path to the center of the earth is less than the radius of the earth, it means that the end-point of the segment is under the horizontal. Consequently, the optical

thickness of the solar path is set to the maximal value. Otherwise, the average atmospheric properties of the solar path, such as the weighted pressure of aerosol, cloud and rain, the average atmospheric pressure and the average density of H<sub>2</sub>O, CO<sub>2</sub> and O<sub>3</sub>, can be calculated. According to the weighted pressure of aerosol, cloud and rain, the interpolation fraction of aerosol, cloud and rain can be calculated through interpolation. However, the average density of H<sub>2</sub>O, CO<sub>2</sub> and O<sub>3</sub> need to be modified as follows.

$$wat = \frac{Avg_{h_2o}}{(Nprof_{h_2o} - 1) \times Avg_{press}} \quad (3)$$

Where  $Avg_{h_2o}$  and  $Avg_{press}$  represent the average density of H<sub>2</sub>O and the average atmospheric pressure. The parameter  $Nprof_{h_2o}$  represents the number of H<sub>2</sub>O profile.

If the condition (a)  $Avg_{h_2o}(i) > wat \times Avg_{press}(i)$  and the condition (b)  $Avg_{press}(i) > Avg_{press}$  are true, the following equation is true.

$$\begin{cases} Ratio = Avg_{press}(i) / Avg_{press} \\ Avg_{h_2o}' = Avg_{h_2o} \times Ratio \\ Avg_{co_2}' = Avg_{co_2} \times Ratio \\ Avg_{o_3}' = Avg_{o_3} \times Ratio \\ Avg_{press}' = Avg_{press} \times Ratio \end{cases} \quad (4)$$

Where  $i$  is an integer and refers to is the index of vertical profile levels. N is the number of vertical profile levels.  $Avg_{h_2o}$ ,  $Avg_{co_2}$  and  $Avg_{o_3}$  represent the average density of H<sub>2</sub>O, CO<sub>2</sub> and O<sub>3</sub> for the unmodified solar path, respectively. The parameter  $Avg_{press}$  represents the average atmospheric pressure for the unmodified solar path.  $Avg_{h_2o}'$ ,  $Avg_{co_2}'$  and  $Avg_{o_3}'$  represent the average density of H<sub>2</sub>O, CO<sub>2</sub> and O<sub>3</sub> for the modified solar path, respectively. The parameter  $Avg_{press}'$  represents the average atmospheric pressure for the modified solar path.  $Avg_{h_2o}(i)$  and  $Avg_{press}(i)$  represent the average density and the average atmospheric pressure of the  $i$ th level. This equation represent that  $i$  traverses the range from 0 to N-1. It judges whether the condition (a) is true or false. If true, the integer  $i$  can be assigned to the condition (b). If the condition (b) is true, the density of H<sub>2</sub>O, CO<sub>2</sub> and O<sub>3</sub> and the average atmospheric pressure for the solar path can be modified by the equation. If the condition (a) is true and the condition (b) is false, there is no need for carrying on modification. If the condition (a) is

always false,  $i$  is assigned to N, then the modification can be carried on.

## 2.5 Molecular Extinction Interpolation Table

Properties of molecular extinction interpolation table are composed of pressure interpolation fraction  $F_{press}$ , H<sub>2</sub>O interpolation fraction  $F_{H_2O}$ , CO<sub>2</sub> interpolation fraction  $F_{CO_2}$ , O<sub>3</sub> interpolation fraction  $F_{O_3}$  and molecular atmospheres  $P_{H_2O}$  ( $P_{H_2O} \leq 4(N_{prof_{H_2O}} + 1)$ ). These properties respectively describe H<sub>2</sub>O, CO<sub>2</sub> and O<sub>3</sub> distribution in the horizontal structure of the atmosphere. For each molecular extinction interval, a multi-dimension interpolation can be performed to determine molecular extinction coefficient. The approach is as follows.

Molecular extinction coefficient in the baseline spectral database is denoted by  $xmol(i, j, m)$ . Where  $i$  is integer and refers to the number of molecular extinction intervals,  $j$  is molecular atmosphere, and  $m$  is the number of vertical profile levels. For some segment, we can determine that it is located in the vertical atmospheric layer  $[m-1, m]$ . For a molecular extinction sub-interval  $i$ , an interpolation is firstly performed using pressure interpolation fraction  $F_{press}$ .

$$xmf[n] = xmol(i, P_{H_2O} + n - 4, m) + F_{press} * [xmol(i, P_{H_2O} + n - 4, m - 1) - xmol(i, P_{H_2O} + n - 4, m)] \quad (5)$$

Where  $n$  is integer and traverses the interval  $[0, 7]$ , the eight values of  $xmf[0] \dots xmf[7]$  can be figured out. Then the next interpolation is performed using O<sub>3</sub> interpolation fraction  $F_{O_3}$ .

$$xmo[n] = xmf[n] + F_{O_3} * (xmf[n+1] - xmf[n]) \quad (6)$$

Where  $n$  traverses the four number of 0, 2, 4 and 6, the four values of  $xmo[0], xmo[2], xmo[4], xmo[6]$  can be also figured out. Then the next interpolation is performed using CO<sub>2</sub> interpolation fraction  $F_{CO_2}$ .

$$xmco[n] = xmo[n] + F_{CO_2} * (xmo[n+2] - xmo[n]) \quad (7)$$

Where  $n$  traverses the two numbers of 0 and 4,  $xmco[0]$  and  $xmco[4]$  can be figured out. Finally the last interpolation is performed H<sub>2</sub>O interpolation fraction  $F_{H_2O}$ .

$$ME = xmco[4] + F_{H_2O} * (xmco[4] - xmco[0]) \quad (8)$$

Where  $ME$  is the molecular extinction coefficient for each segment. In a similar way, the molecular extinction coefficient for solar path can be calculated.

## 2.6 Atmospheric Transmission and Path Radiation

Continua extinction coefficient for each segment remains in all molecular extinction sub-intervals. Assume that  $i$  is the number of molecular extinction sub-interval, and  $j$  is the number of segment. For the  $j$ th segment, its optical depth  $dep_{cn}(j)$  is expressed by the following relation.

$$dep_{cn}(j) = x_{aer} * \rho_{aer} + x_{cld} * \rho_{cld} + x_{rain} * \rho_{rain} \quad (9)$$

Here  $x_{aer}$  refers to aerosol segment spectral extinction,  $x_{cld}$  is cloud segment spectral extinction, and  $x_{rain}$  is rain segment spectral extinction. In addition,  $\rho_{aer}$  is aerosol optical depth,  $\rho_{cld}$  is cloud particle density, and  $\rho_{rain}$  is rain rate in mm/hr raised to 0.63. For the molecular extinction sub-interval  $i$  and the segment  $j$ , the molecular extinction coefficient  $ME(i, j)$  can be calculated by interpolating with molecular extinction interpolation table. Then the total optical depth  $dep_{seg}(i, j)$  can be calculated.

$$dep_{seg}(i, j) = L_{seg}(j) * [dep_{cn}(j) + ME(i, j) * D_{avg}(j)] \quad (10)$$

Where  $L_{seg}(j)$  and  $D_{avg}(j)$  are segment length and average molecular density for the  $j$ th segment, respectively. According to  $\tau = exp(-\sigma * x)$  [4], atmospheric transmission  $T_{seg}(i, j)$  for a molecular extinction sub-interval  $i$  and a segment  $j$  can be also calculated. At this point  $\sigma$  and  $x$  are total optical depth and the length of LOS, respectively. In addition, absorptivity  $A_{seg}(i, j)$  can be also calculated.

$$A_{seg}(i, j) = 1 - T_{seg}(i, j) \quad (11)$$

According to the Planck law, path radiation  $Ems_{seg}(i, j)$  is expressed by the following relation:

$$Ems_{seg}(i, j) = A_{seg}(i, j) * Planck(T_f) + 2[Planck(T_f) - Planck(T_c)] * A_{seg}(i, j) \quad (12)$$

At this point,  $Planck(T_f)$  is the Planck formula,  $T_f$  is the temperature at segment front-point, and  $T_c$  is the temperature at segment center. Next, we can figure out the atmospheric transmission  $T_{seg}(i)$  for the molecular extinction sub-interval  $i$  by applying Beer's Law. The approach is given by:

$$T_{seg}(i) = \prod_{j=0}^{N-1} T_{seg}(i, j) \quad (13)$$

Here  $N$  is the total number of segments in the LOS. More, path radiation  $Ems_{seg}(i)$  for the molecular extinction sub-interval  $i$  can be calculated.

$$Ems_{seg}(i) = \sum_{j=0}^{N-1} [Ems_{seg}(i, j) \times \prod_{k=0}^{j-1} T_{seg}(i, k)] \quad (14)$$

Finally, the total atmospheric transmission  $T_{spec}$  is expressed by the following relation:

$$T_{spec} = \sum_{i=0}^{M-1} [T_{seg}(i) \times W(i)] \quad (15)$$

And the total path radiation  $E_{spec}$  is expressed by the following relation:

$$E_{spec} = \sum_{i=0}^{M-1} [Ems_{seg}(i) \times W(i)] \quad (16)$$

In the two formulas mentioned above,  $M$  is the total number of molecular extinction sub-intervals.  $W(i)$  is the width of the  $i$ th sub-interval.

## 2.7 Single Scattering Solar Radiation

Continua extinction coefficient for solar path at segment front-point remains in all molecular extinction sub-intervals. Assume that  $i$  is the number of molecular extinction sub-interval, and  $j$  is the number of segment. For the  $j$ th segment, its solar optical depth  $deps_{cn}(j)$  is expressed by the following relation:

$$deps_{cn}(j) = x_{xaer} * \rho_{saer} + x_{scld} * \rho_{scld} + x_{srain} * \rho_{srain} \quad (17)$$

Here  $x_{xaer}$  is referring to aerosol solar spectral extinction,  $x_{scld}$  is cloud solar spectral extinction, and  $x_{srain}$  is rain solar spectral extinction. In addition,  $\rho_{saer}$  is aerosol optical depth for solar path,  $\rho_{scld}$  is cloud particle density for solar path, and  $\rho_{srain}$  is rain rate in mm/hr raised to 0.63 for solar path. In addition, the scattering coefficient for the  $j$ th segment can be calculated.

$$S_{seg}(j) = (S_{aer} * \rho_{aer} + S_{cld} * \rho_{cld} + S_{rain} * \rho_{rain}) * P_A(\Psi, g) + S_{mol} * D_{avg}(j) * P_M(\Psi) \quad (18)$$

At this point,  $S_{aer}$  is aerosol segment spectral scattering coefficient,  $S_{cld}$  is cloud segment spectral scattering coefficient,  $S_{rain}$  is rain segment spectral scattering coefficient,  $S_{mol}$  is Raleigh optical depth,  $P_M(\Psi)$  is Henyey-Greenstein formula, and  $P_A(\Psi, g)$  is aerosol scattering phase function[4].

$$P_M(\Psi) = 0.06050402 + 0.0572197 \cos^2 \Psi \quad (19)$$

$$P_A(\Psi, g) = (1 - g^2) / (1 - 2g \cos \Psi + g^2)^{3/2} \quad (20)$$

Here  $\Psi$  is scattering angle, and  $g$  is asymmetry factor. For the molecular extinction sub-interval  $i$  and the segment  $j$ , the molecular extinction coefficient  $SME(i, j)$  for solar path can be calculated by interpolating with molecular extinction interpolation table. Then the total optical depth  $deps_{seg}(i, j)$  for solar path can be calculated.

$$deps_{seg}(i, j) = deps_{cn}(j) + SME(i, j) * D_{avg}(j) \quad (21)$$

Where  $D_{avg}(j)$  is average molecular density over solar path for the  $j$ th segment. According to  $\tau = \exp(-\sigma * x)$ , atmospheric transmission for segment front-point to sun  $T_{sf}(i, j)$  over solar path for the molecular extinction sub-interval  $i$  and the segment  $j$  can be also calculated. At this point  $\sigma$  and  $x$  are total optical depth and the length of LOS, respectively. In a similar way, with reference to the properties of solar path for the next segment, atmospheric transmission for segment end-point to sun can be also figured out. The average l-path transmission through the layer  $T_{sol}(i, j)$  is expressed by the following relation [4].

$$T_{sol}(i, j) = T_{sf}(i, j) \times \int_0^1 \left( \frac{T_{seg}(i, j) \times T_{sb}(i, j)}{T_{sf}(i, j)} \right)^x dx \quad (22)$$

More, single scattering solar radiation coefficient  $SE_{ssct}(i)$  for the molecular extinction sub-interval  $i$  can be calculated.

$$SE_{ssct}(i) = \sum_{j=0}^{N-1} [T_{sol}(i, j) \times S_{seg}(j) \times \prod_{i=0}^{j-1} T_{seg}(i)] \quad (23)$$

Here  $N$  is the total number of segments in the LOS. Finally, the single scattering solar radiation is expressed by the following relation.

$$S_{spec} = I_0 \sum_{i=0}^{M-1} [SE_{ssct}(i) \times W(i)] \quad (24)$$

At this point,  $M$  is the total number of molecular extinction sub-intervals,  $W(i)$  is the width of the  $i$ th sub-interval, and  $I_0$  is solar irradiance of TOA.

## 3 Implementations

The 3D atmospheric radiative transfer model is implemented by object-oriented design method and C++. Figure 3 shows the relationship among the main C++ classes.

The *LineOfSight* class and *LosSegment* class are used to implement line-of-sight and segment in LOS. *BandModel* class defines a general purpose band model which can be used to calculate LOS ratio of atmospheric transmission and path radiation. *SolarBandModel* class is inherited from *BandModel* class and adds calculation of single scattering solar radiation. *MolExtTable* class represents molecular extinction interpolation table and provides method to calculate molecular extinction coefficient. And *ModtranSpectraDb* class encapsulates MODTRAN4 generated spectral database and provides interfaces to access the spectral database. Details of the implementation of the classes are listed below.

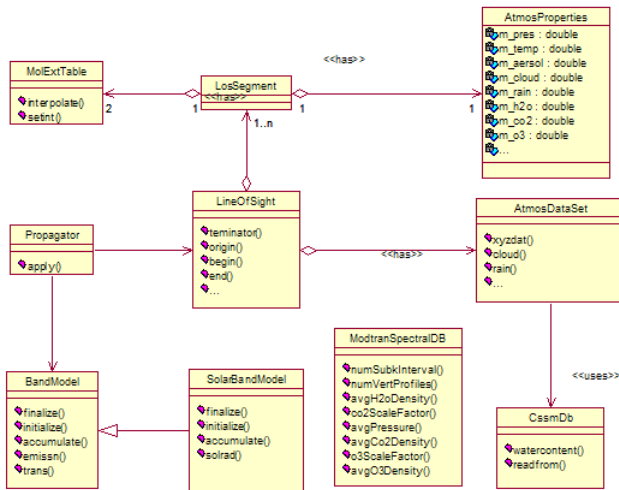


Fig. 3 C++ classes implementation framework

### 3.1 Line-of-sight

Line-of-sight is implemented by *LineOfSight* class which configures the line-of-sight between sensor and target. *LineOfSight* class provides the following operations:

*public:*

```
LineOfSight (const Vector& origin,
             const Vector& terminator,
             unsigned nseglo=5,
             unsigned nseghi=5 );
```

This construct creates and initializes LOS object according to vector *origin* and *terminator*, and then invoke *getlos()* to divide LOS into multiple segments.

*LineOfSight* class uses the following method to get the intersection of LOS and atmosphere boundary, and returns the intersection vector via *bound*. The method is called by *getlos()* to determine each sub-path in LOS:

*private:*

```
void getbnd ( double hbegin,
             const Vector& begin,
             double hend,
             const Vector& end,
             double hbound,
             Vector& bound );
```

The following method calculates the average atmosphere properties:

*private:*

```
void sunsum ( LosSegment&segment,
             AtmosProperties&atmos_properties,
             double& aerp,
             double& cldp,
             double& rainp,
             double& effp,
             double& effh2o,
```

```
double& effco2,
double& effo3 );
```

The following method is called to calculate the optical properties of sun path:

*private:*

```
void sunpath ( const Vector& los0,
              LosSegment& segment,
              AtmosProperties& atmos_properties );
```

The following method is called to set the atmosphere properties and optical properties of segments:

*public:*

```
void losdat ();
```

### 3.2 Segments

*LosSegment* class defines each LOS segments. This class encapsulates properties of segment. The attributes defined by *LosSegment* class are:

*public:*

```
unsigned m_ipasun;// aerosol
unsigned m_ipcsun;//cloud
unsigned m_iprsun;//rain
double m_sunaer;
double m_suncl;
double m_sunrn;
double m_sunden;
double m_fpasun
double m_fpccsun;
double m_fprsun;
MolExtTable m_molext_table;
MolExtTable m_molext_table_sun;
double m_seglen;//length of segment
AtmosProperties m_atmos_properties;
private:
LosSegment *m_next;//point to next segment
```

### 3.3 Single Scattering Solar Radiation

The band model is defined by *BandModel* class and *SolarBandModel* class. *BandModel* class calculates the ratio of atmospheric transmission and path radiation. *SolarBandModel* class inherits from *BandModel* class, and adds calculation of single scattering solar radiation. *BandModel* class provides the following operations:

*public:*

```
virtual void accumulate (const LosSegment&
                        segment,unsigned iv )
{
    //iv represents spectral frequency
    unsigned ipm1=0, intrvl=0;
    double segdep=0.0, segtrn=0.0, segabs=0.0,
           segems=0.0;
```

```

double molExtCoeff = 0.0;
double c2v = 1.43879 * iv;
double c1v3 = ::pow( (1.06E-04*iv), 3.0 );
double bbbnd = Modtran3D::planck( c2v, c1v3,
    segment.m_tband );
//calculate radiation energy in unit volume and unit
//frequency interval
double bbcen = Modtran3D::planck( c2v, c1v3,
    segment.m_atmos_properties.m_temp );
//segment.m_atmos_properties.m_tem p represents
//central segment temperature
//access MODTRAN optical properties in spectral
//database according to band
Modtran3D::ModtranDbRec& db_record =
    Modtran3D::modtran_db.getSpecData( iv );
//calculate continuum optical thickness in segment
double cntdep = segment.xaerp( db_record ) *
    segment.m_atmos_properties.m_aersol
    + segment.xcldp( db_record ) *
    segment.m_atmos_properties.m_cloud
    + segment.xrainp( db_record ) *
    segment.m_atmos_properties.m_rain;
//traverse each molecular extinction segment
ipm1 = segment.m_molext_table.ipres() - 1;
for( intrvl=0; intrvl<m_intrvls; intrvl++ )
{
//calculate molecular extinction coefficient
molExtCoeff =
    segment.m_molext_table.interpolate( intrvl,
    db_record );
segdep = segment.m_seglen* (cntdep +
    segment.m_atmos_properties.m_denpt
    * molExtCoeff);
//store the total optical thickness of each absorbing
//segment
m_cumdep(intrvl) += segdep;
if( segdep < .02 )
{
    segtrn = 1.0 - segdep * (1. - segdep/2);
    segems = segdep * (bbcen+segdep * (bbbnd-4
    * bbcen)/6);
}
else
{
    segtrn = exp(-segdep);
    segabs = 1.0 - segtrn;
    segems = segabs * bbbnd + 2 * (bbcen-bbbnd)
    * (segabs/segdep-segtrn);
}
m_segdep(intrvl) = segdep;
m_segtrn(intrvl) = segtrn;
//calculate path radiation of each molecular
//extinction segment
m_cumems(intrvl) += m_cumtrn(intrvl) *
    segems;
}
}
//called by propogate.apply() function to calculate
//the total value in the absorbing segment
//calculate ratio of transmission in each molecular
//extinction segment
m_cumtrn(intrvl) *= segtrn;
}
}
}
SolarBandModel class calculates LOS single
scattering solar radiation by reloading accumulate()
and finalize () function:
public:
virtual void accumulate (const LosSegment&
    segment, unsigned iv )
{
    ...
    m_iv = iv;
//whether reach the end of the segment
LosSegment* next_segment =
    segment.next_segment();
if( next_segment == 0 )
    return;
//calling the base class to calculate the total path
//radiation
Base::accumulate( segment, iv );
//the local variables are defined below:
int intrvl=0;
double cntdep=0.0;
double cnsdep=0.0, segsct=0;
double deldep=0.0;
double segsol=0.0;
Modtran3D::ModtranDbRec& db_record =
    Modtran3D::modtran_db.getSpecData( iv );
double molExtCoeff = 0.0;
if( m_first_segment )
{
//the continua optical thickness between sensor and
//the sun
m_cnsdep = segment.sun_xaerp( db_record ) *
    segment.m_sunaer
    + segment.sun_xcldp( db_record ) *
    segment.m_suncl
    + segment.sun_xrainp( db_record ) *
    segment.m_sunrn;
//interpolation
for( intrvl=0; intrvl<m_intrvls; intrvl++ )
{
    molExtCoeff =
        segment.m_molext_table_sun.interpolate( in
        trvl, db_record );
    m_sundep(intrvl) = m_cnsdep +
        segment.m_sunden * molExtCoeff;
    m_suntrn(intrvl) = ::exp( -m_sundep(intrvl) );
}
m_first_segment = false;
}
}

```

```

//the continua optical thickness in the sun path
cnsdep = next_segment->sun_xaerp(db_record) *
  next_segment->m_sunaer
+ next_segment->sun_xcldp(db_record) *
  next_segment->m_suncl
+ next_segment->sun_xrainp(db_record) *
  next_segment->m_sunrn;
cntdep = segment.xaerp(db_record) *
  segment.m_atmos_properties.m_aersol;
double gaerp = segment.gaerp(db_record);
segsc = segment.saerp(db_record) *
  segment.m_atmos_properties.m_aersol
* Modtran3D::hengns( gaerp,
  m_los.solScatAngle() )
+ segment.smolp(db_record) *
  segment.m_atmos_properties.m_denpt
* m_los.phaseFunc();
if( segment.m_atmos_properties.m_cloud > 0.0 )
{
//the effort of cloud
  cntdep = cntdep + segment.xcldp(db_record) *
    segment.m_atmos_properties.m_cloud;
  segsc = segsc + segment.scldp(db_record) *
    segment.m_atmos_properties.m_cloud
    *
    Modtran3D::hengns( segment.gcldp(db_rec
ord), m_los.solScatAngle() );
}
if( segment.m_atmos_properties.m_rain > 0. )
{
//the effort of rain
  cntdep = cntdep + segment.xrainp(db_record) *
    segment.m_atmos_properties.m_rain;
  segsc = segsc + segment.srainp(db_record) *
    segment.m_atmos_properties.m_rain
    *
    Modtran3D::hengns( segment.grainp(db_re
cord), m_los.solScatAngle() );
}
segsc = segsc * segment.m_seglen;
//traverse each molecular extinction interval
for( intrvl=0; intrvl<m_intrvls; intrvl++ )
{
  molExtCoeff =
    next_segment->m_molext_table_sun.interpo
late( intrvl, db_record );
  deldep = m_sundep(intrvl);
  segsol = m_suntrn(intrvl);
  m_sundep(intrvl) = cnsdep +
    next_segment->m_sunden * molExtCoeff;
  m_suntrn(intrvl) = exp(-m_sundep(intrvl) );
  deldep = m_sundep(intrvl) + m_segdep(intrvl) -
    deldep;
  if( fabs(deldep) < .001 )
    segsol = ( segsol + m_suntrn(intrvl) *

```

```

  m_segtrn(intrvl))/2;
  else
    segsol = ( segsol - m_suntrn(intrvl) *
      m_segtrn(intrvl))/deldep;
  m_cumsol(intrvl) += m_accumsegtrn(intrvl) *
    segsol * segsc;
  m_accumsegtrn(intrvl) *= m_segtrn(intrvl);
}
}

```

### 3.4 Spectral Database

Spectral database is encapsulated by *ModtranSpectralDB* class. This class processes all the MODTRAN4 generated optical thickness data and general data which will be used by 3D atmospheric radiative transfer model. The mapping table *DbRecClctn* is defined by *typedef std::map<unsigned, ModtranDbRec\*> DbRecClctn* and relates spectral frequency with spectral profile data. The spectral data record *ModtranDbRec* is defined as:

```

struct ModtranDbRec
{
  DoubleArray saer;
  DoubleArray xaer;
  DoubleArray gaer;
  DoubleArray scl;
  DoubleArray xcl;
  DoubleArray gcl;
  DoubleArray srain;
  DoubleArray xrain;
  DoubleArray grain;
  DoubleArray smol;
  DoubleArray xmol; };

```

### 3.5 Molecular Extinction Interpolation Table

Molecular extinction interpolation table is defined by *MolExtTable* class. Molecular extinction coefficient is determined by multiple dimension interpolation. The data member of *MolExtTable* class is correspondent with each attributes of the molecular extinction interpolation table as shown as:

```

class MolExtTable
{
  double m_fpres; //pressure factor
  double m_fh2o; //H2O factor
  double m_fco2; //CO2 factor
  double m_fo3; //O3 factor
}

```

*MolExtTable* class provides operation as:  
public:  
*setint( AtmosProperties& atmos\_data );*



### 3.6 Radiation Transfer Function

*Propagator* class defines the radiation transfer function. This class is an interface class and only has one membership function *apply()* to apply band model to LOS. It is implemented as follows:

```
public:
void apply ( unsigned iv, const LineOfSight& los,
            BandModel& band_model ) const
{
    LineOfSight::const_iterator segItr=los.begin();
    //traverse all the segments in LOS
    for(; segItr!=los.end(); ++segItr )
    {
        band_model.accumulate( *segItr, iv );
    }
    //calculate the total ratio of transmission, path
    radiation and single scattering solar radiation
    band_model.finalize();
}
```

## 4 Results

In order to demonstrate the implementation of the atmospheric inhomogeneities, an experiment has been performed. The new atmospheric model will then be tested at a specific set of points in the scene by comparing the resulting transmission and path radiances to that of a direct MODTRAN result. The focus of this work is on the radiometric effects of the inhomogeneities, not necessarily the accuracy of the spatial structure of them.

A 3DARTM as well as MODTRAN sensor were set up to looking straight down at it through the atmosphere. This would determine the changes in these terms as the target's altitude increases. Settings of model's parameters are following:

- Geographical-seasonal model atmospheres: Mid-Latitude Summer (45 degree North Latitude).
- Aerosol model: RURAL extinction, default VIS=23 km.
- Cloud model: Cumulus cloud layer.
- Sensor's Altitude: 10000 meters.
- Sensor's Waveband: 3-5 micron.

Looking at some sample results in figure 1 and 2, the outputs of both 3DARTM and MODTRAN are compared. These graphs show a spectral average of the path transmission and radiance. As the target approaches the altitude of the sensor, there will be less and less atmosphere between the two. With nothing to get in the way of the photons, it is expected that the transmission will approach unity as the amount of atmosphere between the two approaches zero. This can be seen in figure 4. With less and less

atmosphere to scatter light off of, it is expected that the path radiance will drop to 0, as shown in figure 5.

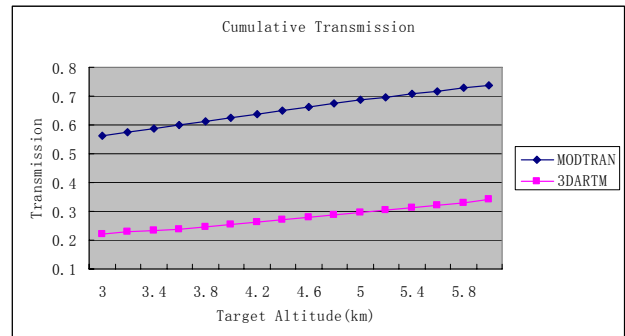


Fig. 4 Change in path transmission as a function of target altitude

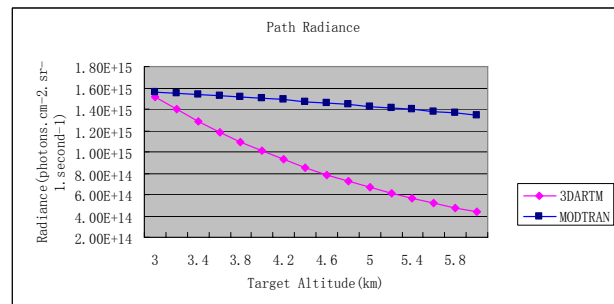


Fig. 5 Change in path radiance as a function of target altitude

## 5 Conclusion

This paper studies the effects of an inhomogeneous atmosphere and the methods involved in modeling its effects. And a 3D atmospheric radiative transfer model has been developed. The 3DARTM can reference an optically different atmosphere depending on its viewing geometry, allowing a horizontally varying atmosphere and it is suited for radiative transfer calculation in a 3D atmosphere. Several results are presented which validate 3DARTM. For more accurate calculation with the model, a lot of work will be needed in future.

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