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A radiative transfer model for atmospheric transmission from target to satellite with geodetic coordinates

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ABSTRACT

A radiative transfer model named TSG (atmospheric transmission from Target to Satellite with Geodetic coordinates) was proposed. Compared with MODTRAN, TSG modifies satellite altitude to 300–36,000 km, geodetic coordinates of target and satellite can be input together in each calculation, zenith and azimuth angle are automatically calculated according to geodetic coordinates of target and satellite and Greenwich Time. Atmospheric transmissions from target to satellite were calculated and analyzed by TSG. And a series of different conditions were used in TSG validation, validation results show that relative differences of average transmittance and integrated radiance between TSG and MODTRAN are less than 1% and 5% in 2000–3000 cm^{-1}, and are less than 8% and 7% in 3000–4000 cm^{-1}, respectively. TSG has good computation accuracy, and it is much more convenient than MODTRAN in calculating atmospheric transmission from target to satellite with geodetic coordinates. The results have important significance in target detecting, tracking and recognition.

1. Introduction

Research on atmospheric transmission from target to satellite has important significance in target detecting, tracking and recognition [1,2]. As is known, it is readily to establish and solving radiative transfer equation in Cartesian coordinate system, however, geodetic coordinate system is recognized as the most convenient coordinate system in remote sensing and GIS. Current radiative transfer model MODTRAN [3–6] is inconvenient in calculating atmospheric transmission from target to satellite with geodetic coordinates for the following reasons: (1) Altitude of target and observer in MODTRAN are 0–100 km, but satellite altitude is much higher than 100 km. (2) Geodetic coordinates of target and observer can't be input together in each calculation in MODTRAN. (3) Zenith and azimuth angle are input parameters in MODTRAN, which are unable to obtain directly in geodetic coordinate system.

In order to solve above problems, a radiative transfer model named TSG (atmospheric transmission from Target to Satellite with Geodetic coordinates) was proposed. With TSG model, satellite altitude is modified to 300–36,000 km, geodetic coordinates of target and satellite can be input together in each calculation, zenith and azimuth angle are automatically calculated according to geodetic coordinates of target and satellite and Greenwich Time. And radiative transfer process is in Cartesian coordinate system in TSG. First, Cartesian coordinates and angle parameters of initial scattering point at top of atmosphere (TOA) were calculated according to geodetic coordinates of target and satellite and Greenwich Time. Second, band model algorithm was used in atmospheric transmittance calculation, and latest calculation method of line tail absorption was employed, upwelled radiative transfer equation (RTE) was solved. Finally, atmospheric transmissions from target to satellite were calculated and analyzed. In TSG validation, angle parameters calculated by TSG were input into MODTRAN, and atmospheric transmissions from target to satellite were calculated and compared by two radiative transfer models.

2. Radiative transfer parameters calculation according to geodetic coordinates

Fig. 1 shows sketch map of target, satellite and earth ellipsoid. (B, L, H) is latitude, longitude and altitude of a point, and (X, Y, Z)

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is Cartesian coordinates of the point. Point E and Point S are target and satellite position, geodetic and Cartesian coordinates of which are (B_E, L_E, H_E), (B_S, L_S, H_S) and (X_E, Y_E, Z_E), (X_S, Y_S, Z_S), respectively. Point M is intersection point of TOA ellipsoid and line ES (LOS), and local zenith of point M is θ.

Point M is the starting position of ray tracing and initial scattering position in TSG, and it is observer point in MODTRAN. Position of point M can be obtained by equation of TOA ellipsoid and LOS. First, equation of earth ellipsoid can be expressed as

$$\frac{X^2+Y^2}{a^2}+\frac{Z^2}{b^2}=1 \tag{1}$$

where a, b is semi-major and semi-minor axis of earth ellipsoid. In TSG, altitude of TOA is set at $h = 100$ km from earth surface, equation of TOA ellipsoid is

$$\frac{X^2+Y^2}{(a+h)^2}+\frac{Z^2}{(b+h)^2}=1 \tag{2}$$

Second, geodetic coordinates of target and satellite are conversed to Cartesian coordinates [7]

$$\begin{cases} X=(N+H)\cos B\cos L \\ Y=(N+H)\cos B\sin L \\ Z=\left[N\left(1-e^2\right)+H\right]\sin B \end{cases} \tag{3}$$

where $N=\frac{a}{\sqrt{1-e^2\sin^2 B}}$, $e=\frac{\sqrt{a^2-b^2}}{a}$ H is altitude of the point.

Direction vector of line ES is $(X_S-X_E, Y_S-Y_E, Z_S-Z_E)$, and Cartesian coordinates of point M (X_M, Y_M, Z_M) can be calculated by equations of space line

$$\begin{cases} X_M=X_E+(X_S-X_E)t \\ Y_M=Y_E+(Y_S-Y_E)t \\ Z_M=Z_E+(Z_S-Z_E)t \end{cases} \tag{4}$$

where t is a parameter. Position of point M also meets equation of TOA ellipsoid, combining Eq. (4) and Eq. (2)

$$\begin{aligned} &\left\{(b+h)^2\left[(X_S-X_E)^2+(Y_S-Y_E)^2\right]+(a+h)^2(Z_S-Z_E)^2\right\}t^2 \\ &+\left\{(b+h)^2\left[2X_E(X_S-X_E)+2Y_E(Y_S-Y_E)\right]+(a+h)^2 2Z_E(Z_S-Z_E)\right\}t \\ &+(b+h)^2\left(X_E{}^2+Y_E{}^2\right)+(a+h)^2 Z_E{}^2-(a+h)^2(b+h)^2=0 \end{aligned} \tag{5}$$

Solution of Eq. (5) is

$$t=\frac{-B_0+\sqrt{B_0{}^2-4A_0C_0}}{2A_0} \tag{6}$$

where $\begin{cases} A_0=(b+h)^2[(X_S-X_E)^2+(Y_S-Y_E)^2]+(a+h)^2(Z_S-Z_E)^2 \\ B_0=(b+h)^2[2X_E(X_S-X_E)+2Y_E(Y_S-Y_E)]+(a+h)^2 2Z_E(Z_S-Z_E) \\ C_0=(b+h)^2(X_E{}^2+Y_E{}^2)+(a+h)^2Z_E{}^2-(a+h)^2(b+h)^2 \end{cases}$.

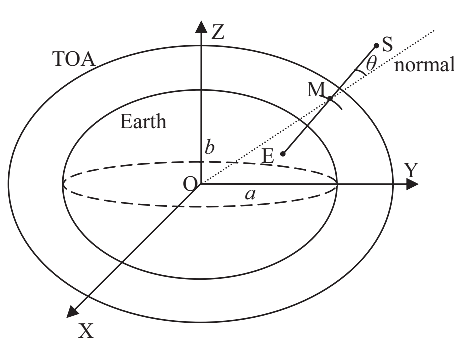

Fig. 1. Sketch map of target, satellite and earth ellipsoid.

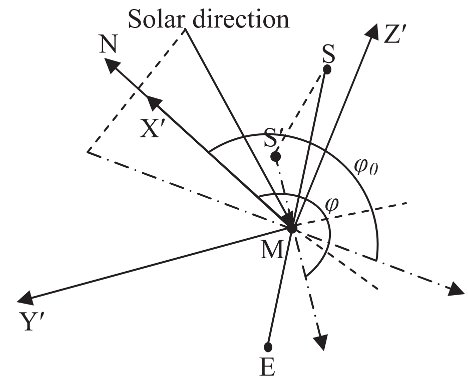

Fig. 2. Azimuth angle defined by horizontal coordinate system.

Finally, Cartesian coordinates of point M is obtained

$$\begin{cases} X_M=X_E+\dfrac{(X_S-X_E)(-B_0+\sqrt{B_0{}^2-4A_0C_0})}{2A_0} \\ Y_M=Y_E+\dfrac{(Y_S-Y_E)(-B_0+\sqrt{B_0{}^2-4A_0C_0})}{2A_0} \\ Z_M=Z_E+\dfrac{(Z_S-Z_E)(-B_0+\sqrt{B_0{}^2-4A_0C_0})}{2A_0} \end{cases} \tag{7}$$

Direction vector of line OM is (X_M, Y_M, Z_M), and local zenith θ of point M is

$$\begin{aligned} \theta &= \arccos\frac{\vec{ES}\cdot\vec{OM}}{\left|\vec{ES}\right|\cdot\left|\vec{OM}\right|} \\ &= \frac{(X_S-X_E)\cdot X_M+(Y_S-Y_E)\cdot Y_M+(Z_S-Z_E)\cdot Z_M}{\sqrt{(X_S-X_E)^2+(Y_S-Y_E)^2+(Z_S-Z_E)^2}\cdot\sqrt{X_M{}^2+Y_M{}^2+Z_M{}^2}} \end{aligned} \tag{8}$$

And then take point M as center point, the horizontal coordinate system (X′Y′Z′) is established and axis X′ is head to the North direction. Point S′ is projection point of point S in X′MY′ plane, φ and φ_0 is azimuth angle of point M and solar direction, shown in Fig. 2.

3. Atmospheric transmission from target to satellite

When satellite is in straight (or slant) overlook mode, plane-parallel atmospheric model is usually applied [8]. But in order to increase computation accuracy, spherical atmospheric model is applied in TSG, and atmosphere is divided into concentric spherical shells.

Band model algorithm is used in transmittance calculation, and molecular band model parameters used by TSG is from MODTRAN database based on HITRAN2008 [9,10]. Twelve kinds of molecular species are considered, including H_2O, CO_2, O_3, N_2O, CO, CH_4, etc. For each species of molecular, absorption transmittance is calculated by band model algorithm [11]

$$t_{abs}=\left(1-\left\langle W_{sl}\right\rangle/\Delta\nu\right)^{\langle n\rangle}\cdot\exp\left[-\sum_l (C)_l(\Delta u)_l\right] \tag{9}$$

where $\left\langle W_{sl}\right\rangle$ is the Voigt single-line equivalent width for the line-strength distribution in a spectral interval, and C–G approximation is used to calculation $\left\langle W_{sl}\right\rangle$.$\langle n\rangle$ is the path-averaged effective number of lines in the bin, $\langle n\rangle=\Delta\nu\left\langle 1/d\right\rangle$, l is atmosphere layers. The line tail absorption is fit to temperature and pressure dependent Padé approximants, and latest calculation method of line tail absorption is employed [12]. In order to increase calculation