Upper estimate of the error of using equations for the total irradiance at the surface point

A) Consider simplified equation for the total irradiance at the surface point:

$$\widetilde{E_{sum,1}} = \frac{E_0}{1-\overline{r_{surf}}\gamma_1} = E_0 + E_0\overline{r_{surf}}\gamma_1 + E_0\left(\overline{r_{surf}}\gamma_1\right)^2 + \ldots \quad (1)$$

where E_0 is the irradiance of the ground surface for a non-reflective ground surface; $\overline{r_{surf}}$ is the reflectance averaged over the observed surface fragment in the approximation of the uniform surface; γ_1 is the spherical albedo of the atmosphere.

Without any assumptions, the value of E_{sum} value can be written as follows:

$$E_{sum} =$$

$$E_0 + E_0 \iint_S r_{surf}(x'_w, y'_w) h_1(x_w, y_w, x'_w, y'_w) dx'_w dy'_w +$$

$$E_0 \iint_S r_{surf}(x'_w, y'_w) \left[\iint_S r_{surf}(x''_w, y''_w) h_1(x'_w, y'_w, x''_w, y''_w) dx''_w dy''_w\right] h_1(x_w, y_w, x'_w, y'_w) dx'_w dy'_w + \ldots \quad (2)$$

where (x'_w, y'_w), (x''_w, y''_w) are the surface coordinates; S – spherical ground surface; h_1 is Point Spread Function (PSF) of the additional surface irradiance formation.

Consider the Δ_1 value:

$$\Delta_1 \equiv \frac{\left|E_{sum} - \widetilde{E_{sum,1}}\right|}{E_0} \leq$$

$$\frac{\left|E_0 \iint_S r_{surf}(x'_w, y'_w) h_1(x_w, y_w, x'_w, y'_w) dx'_w dy'_w - E_0\overline{r_{surf}}\gamma_1\right|}{E_0} +$$

$$\frac{\left|E_0 \iint_S r_{surf}(x'_w, y'_w)\left[\iint_S r_{surf}(x''_w, y''_w) h_1(x'_w, y'_w, x''_w, y''_w) dx''_w dy''_w\right] h_1(x_w, y_w, x'_w, y'_w) dx'_w dy'_w - E_0\left(\overline{r_{surf}}\gamma_1\right)^2\right|}{E_0} + \cdots \leq$$

$$\leq \frac{E_0 max\left|r_{surf}(x_w, y_w) - \overline{r_{surf}}\right|\gamma_1}{E_0} + \frac{E_0 max\left|r_{surf}(x_w, y_w)^2 - \overline{r_{surf}}^2\right|{\gamma_1}^2}{E_0} + \cdots \quad (3)$$

In the limiting cases, the quantities $\overline{r_{surf}}$ are small. Then the upper limit for Δ_1 is:

$$\Delta_1 \leq \frac{r_{surf,max}\gamma_1}{1 - r_{surf,max}\gamma_1} \quad (4)$$

where $r_{surf,max}$ is the maximal value of the surface reflectance over the considered surface fragment.

B) Similarly, consider equation for the total irradiance at the surface point for proposed algorithm:

$$\widetilde{E_{sum,2}} = E_0 + E_0 \sum_{k=1}^{N_i} \sum_{l=1}^{N_j} r_{surf,kl} h_1\left(r_{w,ijkl}\right) S_{kl} + E_0 C_{out}\left(\varphi_{N,ij}, \lambda_{N,ij}\right)\overline{r_{surf}} + \frac{E_0\left(\overline{r_{surf}}\gamma_1\right)^2}{1-\overline{r_{surf}}\gamma_1} \quad (5)$$

$$C_{out}\left(\varphi_{N,ij}, \lambda_{N,ij}\right) = 2\pi \int_0^{\pi R_e} h_1(r_w) dr_w - \sum_{k=1}^{N_k} \sum_{l=1}^{N_l} h_1\left(r_{w,ijkl}\right) \quad (6)$$

where $r_{surf,kl}$ is ground surface reflectance for the pixel (k,l); S_{kl} is the area of the pixel in the k-th line and l-th column of the considered fragment; $r_{w,ijkl}$ is the distance from the point with coordinates $\varphi_{N,ij}$, $\lambda_{N,ij}$ to the point with coordinates $\varphi_{N,kl}$, $\lambda_{N,kl}$ along the ground surface; dr_w is the differential of the distance over the spherical ground surface; R_e is the radius of the Earth.

Consider the Δ_2 value:

$$\Delta_2 \equiv \frac{|E_{sum}-\widetilde{E_{sum,2}}|}{E_0} = \frac{\left|E_{sum}-E_0-E_0\sum_{k=1}^{N_i}\sum_{l=1}^{N_j} r_{surf,kl}h_1(r_{w,ijkl})S_{kl}-E_0C_{out}\left(\varphi_{N,ij},\lambda_{N,ij}\right)\overline{r_{surf}}-\frac{E_0\left(\overline{r_{surf}}\gamma_1\right)^2}{1-\overline{r_{surf}}\gamma_1}\right|}{E_0} \leq$$

$$\frac{\left|E_0-E_0+E_0\iint_S r_{surf}(x_w',y_w')h_1(x_w,y_w,x_w',y_w')dx_w'dy_w'-E_0\sum_{k=1}^{N_i}\sum_{l=1}^{N_j} r_{surf,kl}h_1(r_{w,ijkl})S_{kl}-E_0C_{out}\left(\varphi_{N,ij},\lambda_{N,ij}\right)\overline{r_{surf}}\right|}{E_0} +$$

$$\frac{E_0\left|\iint_S r_{surf}(x_w',y_w')\left[\iint_S r_{surf}(x_w',y_w')h_1(x_w',y_w',x_w',y_w')dx_w'dy_w'\right]h_1(x_w,y_w,x_w',y_w')dx_w'dy_w'-\left(\overline{r_{surf}}\gamma_1\right)^2\right|}{E_0} + \cdots \leq$$

$$\frac{E_0 max\left|r_{surf}(x_w',y_w')^2-\left(\overline{r_{surf}}\right)^2\right|}{E_0} + \cdots \qquad (7)$$

In the limiting case, the upper limit for the quantity Δ_2 is:

$$\Delta_2 \leq \frac{\left(r_{surf,max}\gamma_1\right)^2}{1-r_{surf,max}\gamma_1} \qquad (8)$$

C) In the article [Lenoble J. Modeling of the Influence of Snow Reflectance on Ultraviolet Irradiance for Cloudless Sky // Appl. Opt. 1998. V. 37. P. 2441–2447.], it was found that at λ=0.4 μm for the molecular atmosphere, γ_1=0.24, which coincides with the results of our calculations for the same atmospheric model. Substituting γ_1=0.24 and $r_{surf,max}$=0.4 to the Eq. (4) and (8) we obtain $\Delta_1 \leq 0.106$ and $\Delta_2 \leq 0.01$. At $AOD_{0.55}$=7 we obtain at λ=0.4 μm that γ_1 ~ 0.4. Then $\Delta_1 \leq 0.19$ and $\Delta_2 \leq 0.03$. Below we present the vertical profiles of atmospheric parameters used for these calculations.

Case 1. Molecular atmosphere

λ=0.4 μm

	Altitude,km		Aerosol extinction,km-1		Aerosol scattering,km-1	Molecular extinction,km-1	Molecular scattering,km-1
1	0.000	1.000	0	0	0.39634E-01	0.39634E-01	
2	1.000	2.000	0	0	0.35818E-01	0.35818E-01	
3	2.000	3.000	0	0	0.32370E-01	0.32370E-01	
4	3.000	4.000	0	0	0.29266E-01	0.29266E-01	
5	4.000	5.000	0	0	0.26426E-01	0.26426E-01	
6	5.000	6.000	0	0	0.23801E-01	0.23801E-01	
7	6.000	7.000	0	0	0.21377E-01	0.21377E-01	
8	7.000	8.000	0	0	0.19167E-01	0.19167E-01	
9	8.000	9.000	0	0	0.17159E-01	0.17159E-01	
10	9.000	10.000	0	0	0.15318E-01	0.15318E-01	
11	10.000	11.000	0	0	0.13634E-01	0.13634E-01	
12	11.000	12.000	0	0	0.12098E-01	0.12098E-01	
13	12.000	13.000	0	0	0.10692E-01	0.10692E-01	
14	13.000	14.000	0	0	0.92904E-02	0.92904E-02	
15	14.000	15.000	0	0	0.79199E-02	0.79199E-02	
16	15.000	16.000	0	0	0.67454E-02	0.67454E-02	
17	16.000	17.000	0	0	0.57661E-02	0.57661E-02	
18	17.000	18.000	0	0	0.49196E-02	0.49196E-02	
19	18.000	19.000	0	0	0.41865E-02	0.41865E-02	

20	19.000	20.000	0	0	0.35640E-02	0.35640E-02
21	20.000	21.000	0	0	0.30356E-02	0.30356E-02
22	21.000	22.000	0	0	0.25874E-02	0.25874E-02
23	22.000	23.000	0	0	0.22095E-02	0.22095E-02
24	23.000	24.000	0	0	0.18870E-02	0.18870E-02
25	24.000	25.000	0	0	0.16113E-02	0.16113E-02
26	25.000	30.000	0	0	0.10344E-02	0.10344E-02
27	30.000	35.000	0	0	0.48008E-03	0.48008E-03
28	35.000	40.000	0	0	0.22926E-03	0.22926E-03
29	40.000	45.000	0	0	0.11329E-03	0.11329E-03
30	45.000	50.000	0	0	0.58359E-04	0.58359E-04
31	50.000	70.000	0	0	0.15720E-04	0.15720E-04
32	70.000	100.000	0	0	0.68224E-06	0.68224E-06

Case 2 Turbid atmosphere

λ=0.4 μm

	Altitude,km		Aerosol extinction,km-1	Aerosol scattering,km-1	Molecular extinction,km-1	Molecular scattering,km-1
1	0.000	1.000	5.5336	5.2620	0.39634E-01	0.39634E-01
2	1.000	2.000	1.3161	1.2515	0.35818E-01	0.35818E-01
3	2.000	3.000	0.69581E-01	0.66518E-01	0.32370E-01	0.32370E-01
4	3.000	4.000	0.37774E-01	0.36443E-01	0.29266E-01	0.29266E-01
5	4.000	5.000	0.19659E-01	0.18966E-01	0.26426E-01	0.26426E-01
6	5.000	6.000	0.12464E-01	0.12024E-01	0.23801E-01	0.23801E-01

7	6.000	7.000	0.10200E-01	0.98404E-02	0.21377E-01	0.21377E-01
8	7.000	8.000	0.68371E-02	0.65961E-02	0.19167E-01	0.19167E-01
9	8.000	9.000	0.36957E-02	0.35655E-02	0.17159E-01	0.17159E-01
10	9.000	10.000	0.21352E-02	0.20600E-02	0.15318E-01	0.15318E-01
11	10.000	11.000	0.14407E-02	0.14112E-02	0.13634E-01	0.13634E-01
12	11.000	12.000	0.10832E-02	0.10832E-02	0.12098E-01	0.12098E-01
13	12.000	13.000	0.87124E-03	0.87124E-03	0.10692E-01	0.10692E-01
14	13.000	14.000	0.72282E-03	0.72282E-03	0.92904E-02	0.92904E-02
15	14.000	15.000	0.63149E-03	0.63149E-03	0.79199E-02	0.79199E-02
16	15.000	16.000	0.58678E-03	0.58678E-03	0.67454E-02	0.67454E-02
17	16.000	17.000	0.60950E-03	0.60950E-03	0.57661E-02	0.57661E-02
18	17.000	18.000	0.71372E-03	0.71372E-03	0.49196E-02	0.49196E-02
19	18.000	19.000	0.83154E-03	0.83154E-03	0.41865E-02	0.41865E-02
20	19.000	20.000	0.88365E-03	0.88365E-03	0.35640E-02	0.35640E-02
21	20.000	21.000	0.82224E-03	0.82224E-03	0.30356E-02	0.30356E-02
22	21.000	22.000	0.69451E-03	0.69451E-03	0.25874E-02	0.25874E-02
23	22.000	23.000	0.53871E-03	0.53871E-03	0.22095E-02	0.22095E-02
24	23.000	24.000	0.37080E-03	0.37080E-03	0.18870E-02	0.18870E-02
25	24.000	25.000	0.24501E-03	0.24501E-03	0.16113E-02	0.16113E-02
26	25.000	30.000	0.10762E-03	0.10762E-03	0.10344E-02	0.10344E-02
27	30.000	35.000	0.33578E-04	0.33556E-04	0.48008E-03	0.48008E-03
28	35.000	40.000	0.12129E-04	0.12096E-04	0.22926E-03	0.22926E-03

29	40.000	45.000	0.59871E-05	0.59709E-05	0.11329E-03	0.11329E-03
30	45.000	50.000	0.30622E-05	0.30539E-05	0.58359E-04	0.58359E-04
31	50.000	70.000	0.78146E-06	0.77936E-06	0.15720E-04	0.15720E-04
32	70.000	100.000	0.32052E-07	0.31966E-07	0.68224E-06	0.68224E-06

AEROSOL PHASE FUNCTION:

Cosines of the scattering angles

1.0000 0.9994 0.9976 0.9945 0.9903 0.9848 0.9781 0.9613 0.9397 0.9135 0.8829 0.8480 0.8090 0.7660 0.6428 0.5000 0.3420 0.1736 0.0000 -0.1736 -0.3420 -0.5000 -0.5736 -0.6428 -0.7071 -0.7660 -0.8192 -0.8660 -0.9063 -0.9397 -0.9659 -0.9848 -0.9962 -1.0000

Layer number Aerosol phase function for a given cosine of the scattering angle

1 152.49 18.550 9.7361 7.2998 6.0878 5.2807 4.6587 3.7015 2.9679 2.3856 1.9195 1.5472 1.2494 1.0117 0.60657 0.37523 0.24144 0.16372 0.11751 0.90201E-01 0.75479E-01 0.69099E-01 0.68391E-01 0.69284E-01 0.71744E-01 0.75981E-01 0.82087E-01 0.90018E-01 0.99097E-01 0.10643 0.11043 0.11518 0.13015 0.13971

2 137.55 18.858 9.7521 7.1895 5.9456 5.1440 4.5403 3.6243 2.9243 2.3653 1.9146 1.5516 1.2592 1.0242 0.61978 0.38606 0.24962 0.16976 0.12210 0.93903E-01 0.78614E-01 0.71926E-01 0.71113E-01 0.71903E-01 0.74268E-01 0.78358E-01 0.84251E-01 0.91909E-01 0.10073 0.10823 0.11262 0.11796 0.13292 0.14232

3 73.538 13.069 8.2003 6.6355 5.7441 5.0914 4.5563 3.6874 2.9951 2.4333 1.9765 1.6066 1.3076 1.0665 0.64979 0.40739 0.26515 0.18113 0.13097 0.10138 0.85197E-01 0.78108E-01 0.77257E-01 0.78094E-01 0.80576E-01 0.84734E-01 0.90577E-01 0.97838E-01 0.10574 0.11240 0.11712 0.12497 0.14270 0.15451

4 7.3394 7.0826 6.5956 6.0627 5.5358 5.0370 4.5729 3.7527 3.0683 2.5035 2.0405 1.6634 1.3575 1.1102 0.68083 0.42945 0.28121 0.19288 0.14014 0.10911 0.92004E-01 0.84500E-01 0.83611E-01 0.84496E-01 0.87098E-01 0.91327E-01 0.97118E-01 0.10397 0.11092 0.11671 0.12176 0.13223 0.15281 0.16711

5 7.3394 7.0826 6.5956 6.0627 5.5358 5.0370 4.5729 3.7527 3.0683 2.5035 2.0405 1.6634 1.3575 1.1102 0.68083 0.42945 0.28121 0.19288 0.14014 0.10911 0.92004E-01 0.84500E-01 0.83611E-01 0.84496E-01 0.87098E-01 0.91327E-01 0.97118E-01 0.10397 0.11092 0.11671 0.12176 0.13223 0.15281 0.16711

6 7.3394 7.0826 6.5956 6.0627 5.5358 5.0370 4.5729 3.7527 3.0683 2.5035 2.0405 1.6634 1.3575 1.1102 0.68083 0.42945 0.28121 0.19288 0.14014 0.10911 0.92004E-01 0.84500E-01 0.83611E-01 0.84496E-01 0.87098E-01 0.91327E-01 0.97118E-01 0.10397 0.11092 0.11671 0.12176 0.13223 0.15281 0.16711

7 7.3394 7.0826 6.5956 6.0627 5.5358 5.0370 4.5729 3.7527 3.0683 2.5035 2.0405 1.6634 1.3575 1.1102 0.68083 0.42945 0.28121 0.19288 0.14014 0.10911 0.92004E-01 0.84500E-01 0.83611E-01 0.84496E-01 0.87098E-01 0.91327E-01 0.97118E-01 0.10397 0.11092 0.11671 0.12176 0.13223 0.15281 0.16711

8 7.3394 7.0826 6.5956 6.0627 5.5358 5.0370 4.5729 3.7527 3.0683 2.5035 2.0405 1.6634 1.3575 1.1102 0.68083 0.42945 0.28121 0.19288 0.14014 0.10911 0.92004E-01 0.84500E-01 0.83611E-01 0.84496E-01 0.87098E-01 0.91327E-01 0.97118E-01 0.10397 0.11092 0.11671 0.12176 0.13223 0.15281 0.16711

9 7.3394 7.0826 6.5956 6.0627 5.5358 5.0370 4.5729 3.7527 3.0683 2.5035 2.0405 1.6634 1.3575 1.1102 0.68083 0.42945 0.28121 0.19288 0.14014 0.10911 0.92004E-01 0.84500E-01 0.83611E-01 0.84496E-01 0.87098E-01 0.91327E-01 0.97118E-01 0.10397 0.11092 0.11671 0.12176 0.13223 0.15281 0.16711

10 7.3394 7.0826 6.5956 6.0627 5.5358 5.0370 4.5729 3.7527 3.0683 2.5035 2.0405 1.6634 1.3575 1.1102 0.68083 0.42945 0.28121 0.19288 0.14014 0.10911 0.92004E-01 0.84500E-01 0.83611E-01 0.84496E-01 0.87098E-01 0.91327E-01 0.97118E-01 0.10397 0.11092 0.11671 0.12176 0.13223 0.15281 0.16711

11 10.514 9.5985 8.4881 7.4744 6.5775 5.7940 5.1136 4.0097 3.1695 2.5211 2.0153 1.6178 1.3035 1.0544 0.63356 0.39410 0.25550 0.17402 0.12580 0.97618E-01 0.82124E-01 0.75514E-01 0.75008E-01 0.76272E-01 0.79432E-01 0.84692E-01 0.92235E-01 0.10186 0.11256 0.12147 0.12493 0.12929 0.14780 0.16481

12 13.691 12.116 10.382 8.8870 7.6200 6.5514 5.6547 4.2669 3.2707 2.5387 1.9900 1.5721 1.2494 0.99860 0.58626 0.35873 0.22976 0.15514 0.11146 0.86122E-01 0.72237E-01 0.66523E-01 0.66399E-01 0.68042E-01 0.71761E-01 0.78053E-01 0.87348E-01 0.99750E-01 0.11420 0.12623 0.12809 0.12635 0.14279 0.16252

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17 13.691 12.116 10.382 8.8870 7.6200 6.5514 5.6547 4.2669 3.2707 2.5387 1.9900 1.5721 1.2494 0.99860 0.58626 0.35873 0.22976 0.15514 0.11146 0.86122E-01 0.72237E-01 0.66523E-01 0.66399E-01 0.68042E-01 0.71761E-01 0.78053E-01 0.87348E-01 0.99750E-01 0.11420 0.12623 0.12809 0.12635 0.14279 0.16252

18 13.691 12.116 10.382 8.8870 7.6200 6.5514 5.6547 4.2669 3.2707 2.5387 1.9900 1.5721 1.2494
0.99860 0.58626 0.35873 0.22976 0.15514 0.11146 0.86122E-01 0.72237E-01 0.66523E-01 0.66399E-01 0.68042E-01 0.71761E-01
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19 13.691 12.116 10.382 8.8870 7.6200 6.5514 5.6547 4.2669 3.2707 2.5387 1.9900 1.5721 1.2494
0.99860 0.58626 0.35873 0.22976 0.15514 0.11146 0.86122E-01 0.72237E-01 0.66523E-01 0.66399E-01 0.68042E-01 0.71761E-01
0.78053E-01 0.87348E-01 0.99750E-01 0.11420 0.12623 0.12809 0.12635 0.14279 0.16252

20 13.691 12.116 10.382 8.8870 7.6200 6.5514 5.6547 4.2669 3.2707 2.5387 1.9900 1.5721 1.2494
0.99860 0.58626 0.35873 0.22976 0.15514 0.11146 0.86122E-01 0.72237E-01 0.66523E-01 0.66399E-01 0.68042E-01 0.71761E-01
0.78053E-01 0.87348E-01 0.99750E-01 0.11420 0.12623 0.12809 0.12635 0.14279 0.16252

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