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Contribution of the Intensity of Scattered Light for each Wavelength to the Sky Light at Daytime

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Abstract

Using the author's method for the scattering problem considering the earth's atmosphere of 40 km depth, composed of $4 \times 10^4$ numbers of homogeneous spherical shell of 1 m thickness by calculating the atmospheric density by the accuracy of 1 m of height he has computed the intensity resulting respectively from the primary and secondary scattering coming from all portions in the sky dome to a point on the earth's surface, and accordingly the sky radiation received on a horizontal surface at the point. The computed results are compared with Sekera's obtained by means of Chandrasekhar's solution for the radiative transfer problem in a plane-parallel model of the earth's atmosphere with respect to the horizontal surface. The author's relative horizontal intensity resulting only from the primary scattering (i.e. in the unit of the extraterrestrial solar radiation at the corresponding wavelength) has the same feature of dependency to the wavelength and solar zenith distance with the result given by Sekera. The author's relative horizontal intensity resulting from only the secondary scattering has also the same feature of dependency to the wavelength and solar zenith distance with the result given by Sekera. The integrated relative horizontal global radiation for the whole range of wavelength is in good agreement with Sekera's in the range of zenith distance $0^\circ \sim 90^\circ$, in such a way that one cannot discriminate both curves on the graph.

Introduction

As Sekera says, several attempts have been made in the past to evaluate the amount and the spectral distribution of the radiation received by the earth's
surface, which are essential in all problems dealing with the radiational effects in the atmosphere, from theoretical considerations.

However, in 1950, S. Chandrasekhar developed a method basing on the problems of radiative transfer, in solving all orders of scattering in a plane parallel atmosphere of infinite lateral extent but of finite depth. The density is assumed to depend only on height above the ground.

Dr. Sekera introduced a remarkable and laborious calculation in the global radiation in 1954. Sato has computed the radiation by numerical integration neglecting all orders of scattering higher than the third as explained in this paper.

1. Primary scattering

Let O be the earth's centre and O' be any point on its surface. Take axes \(X', Y', Z'\) with the origin at \(O'\) as shown in Fig. 1. \(Z'\) is directed towards \(O O'\), i.e. zenith and \(X'\) is normal to \(Z'\) and lies in the sun's side in the plane containing \(Z'\) and the sun's centre. \(Y'\) is normal to \(X'Z'\) plane. Take a point \(E\) in the sky dome with its centre at \(O'\), and define its distance from \(O'\) by \(R\), the altitude by \(\theta\), the azimuth measured from \(Y'\) by \(A\). Then its coordinates becomes

\[
X' = R \cos \theta \cos A \\
Y' = R \cos \theta \sin A \\
Z' = R \sin \theta
\]

(1)

Fig. 1. \(X Y Z\) coordinate system and angles \(A, \theta\).

Let \(\varphi\) be the angle between \(OE\) and solar ray passing through \(E\), and \(h\) be the sun's altitude at \(O'\). Then

\[
\cos \varphi = \sin \theta \sin h + \cos \theta \cos h \cos A
\]

(2)

Let \(M_{OE}\) be the amount of air mass traversed by the solar ray from the upper limit of the atmosphere to \(E\), \(M_E\) the mass between \(E\) and \(O'\) and \(\rho_E\) the air density at \(E\), then

\[
\frac{3}{16\pi R^2} \left(1 + \cos^2 \varphi\right) e^{-k(M_{OE} + M_E)} \cdot \frac{I_0}{D^2}
\]

(3)

is the amount of primary scattering received by \(O'\) from an air portion exposed
to the direct solar ray of unit depth bounded by one steradian of cone with its axis at $OE$ and vertex at $O'$, in which $I_0$ is the solar constant and $D$ the distance of the earth from the sun.

2. Secondary scattering

Consider a point $T$ exposed to the direct solar ray in the atmosphere which can be seen from $E$. Now take a coordinate system $XYZ$ at the origin $O$, which is parallel to $X'Y'Z'$ system.

![Fig. 2. X Y Z coordinate system and angles $A, \gamma$.](image)

Let $\angle OET = \theta_1$, $ET = r$ and $A_1$ be the azimuth of $OT$ measured from the axis $x_2$ of the coordinate system $x_2y_2z_2$ defined by the following relation to $XYZ$:

$$
egin{align*}
X &= \cos \gamma \cos A - \sin A \sin \gamma \cos A \\
Y &= \cos \gamma \sin A + \cos A \sin \gamma \sin A \\
Z &= \sin \gamma \\
\end{align*}
$$

Let $\varphi_T$ be the amount of air mass traversed by the solar ray from the upper limit of the atmosphere to $T$, $M_T$ the mass between $T$ and $E$, $\rho_T$ the air density at $T$, $r$, the distance from $E$ to the earth's surface or the limit of upper atmosphere on the straight line directed from $E$ to $T$ and $\varphi$ the polarization.
angle of secondary scattering, then we have the following amount of secondary scattering received by $O'$ from the same air portion at $E$ as the primary scattering introduced in (4), whose portion in this case is exposed to the primary scattering from an air portion of a cone of one steradian whose vertex is $E$ and axis $ET$:

$$
\frac{1}{2} \left( \frac{3}{8\pi} \right)^2 k^2 \rho E \frac{I_0}{D^2} \int_0^{T_1} \psi e^{-M_{EX}} \int_0^{\psi} e^{-(M_{ET}+M_{OT})} \, d\psi
$$

In this formula $\psi$ is a function of $\theta, A, \theta_1, A_1$, but is independent of the position of $T$ on $ET$ i.e. of $r$.

3. Value of $k$

$k$ is an amount inversely proportional to the fourth power of wavelength $\lambda$. Let $\rho$ be the transmission coefficient of the atmosphere of depth $l$, then

$$
\rho = \exp \left( \int_0^l k \rho \, dx \right)
$$

in which $\rho$ is the air density at the height $x$ from the surface.

Let $M_0$ be the total mass of vertical air column of unit cross section, so

$$
\rho = e^{-kM_0}
$$

Now the direct solar ray, the primarily and secondarily scattered rays are traversing the air mass in the sky. Let $i_o$ be the intensity of incident ray and $M$ the traversed mass, then the intensity after passing the air mass becomes

$$
i = i_o e^{-kM/M_0} = i_o \rho M/M_0
$$

Eq. (7) shows that $\rho$ also varies by $\lambda$. Let $I_o\lambda$ be the solar radiation intensity of wavelength $\lambda$ at the sun’s means distance, and $I_o$ the total intensity, then

$$
\int_0^\infty I_o\lambda d\lambda = I_o
$$

Now we divide the total energy into twelve parts of the ranges $0 \sim \lambda_1, \lambda_1 \sim \lambda_2 \cdots \lambda_1, \sim \infty$ such that the partial energy in each range is equal:

$$
\int_0^{\lambda_1} I_o\lambda d\lambda = \int_{\lambda_1}^{\lambda_2} I_o\lambda d\lambda = \int_{\lambda_2}^{\lambda_3} I_o\lambda d\lambda = \cdots = \int_{\lambda_{11}}^{\infty} I_o\lambda d\lambda = \frac{1}{12} I_o
$$

From the accurate intensity distribution of solar radiation in Linke’s Taschenbuch, we get the value $\lambda_i$ in Table 1, assuming

$$
I_o = 1.940 \text{ cal cm}^{-2} \text{ min}^{-1}
$$

From the transmission coefficient $\rho$, and the radiation intensity for each wavelength in the literature, we can compute the transmission coefficient for
the above domains by

\[ p_1 = \frac{\int_{\lambda_1}^{\lambda_{l+1}} p_{1,1} I_{e,1} d\lambda}{\int_{\lambda_1}^{\lambda_{l+1}} I_{e,1} d\lambda} \]  

(11)
as shown in Table 1.

From (7) we get the value of \( k \) for each domain as shown in \( k_1 \) in Table 1, from (7) and (11).

4. Method to evaluate the mass traversed by the ray

The formulae (3) and (5) can be applied for each wavelength domain by substituting \( k_1 \) for \( k \) and \( I_e/12 \) for \( I_o \). The results thus obtained might be expressed by (12) and (13). We must now evaluate the value

\[ e^{-k_1(M_{E,T}+M_{E})} \quad \text{and} \quad e^{-k_1(M_{E,T}+M_{OT})} \]
in these formulae. For brevity, the quantity in parenthesis is denoted by \( \Sigma M \).

Hence

\[ e^{-k_1\Sigma M} = p_1 e^{\Sigma M/M_0} \]  

(14)
So the evaluation of \( \Sigma M \) in \( M_0 \) unit is necessary.

For this purpose we must obtain the mass between two points \( T \) and \( E \), and \( E \) and \( O' \) and the mass passed by the direct solar ray.

We have computed the mass from a point on the earth's surface to a point at any height, including the limit of upper atmosphere (40km level), on a line starting from that point on the surface to the following zenith distances:

- 30°, 60°, 65°, 70°, 75°, 76°, 79°, 80°, 81°, 82°, 83°, 84°, 85°, 86°, 86°20', 86°40', 87°00', 87°20', 87°40', 88°00', 88°40', 89°00', 89°10', 89°20', 89°30', 89°40', 89°50', 90°

The Table and graph thus computed are called A Table and A Graph respectively for convenience of reference, though not presented in this paper, from which the value of \( M_E \) can be given.

When the line connecting two points \( E \) and \( T \) intersects with the earth's surface, we can get the mass between both points by the above Table and Graph as follows.

Let the intersecting point of the line with the surface be \( O^* \) and the angle between \( OO^* \) and the line be \( z \), then \( z \) can be obtained form

\[ \sin z = \frac{OE}{a_o} \sin \theta_1 \]  

(15)
\( a_0 \) being the earth's radius 6370 km.

From \( z \) and the height of \( E \) and \( T \), we can gain the mass between \( O'E \)
and \( O'T \) from A Table and A Graph, so the mass between \( E \) \( T \) can be given
as the difference of the two.

When \( z \leq 60^\circ \), this traversed mass can be got by the vertical mass between
the two heights multiplied by \( \sec z \) with negligible error. If the right hand side
of (15) is larger than 1, the line \( ET \) cannot intersect with the earth.

In this case the following method is preferable. Evaluate the mass from a
point at the height of 1,2,3,\ldots,38,39km to a point at any height on a line
starting horizontally from the former point. By this task we have a Table
and a graph denoted by B Table and B Graph respectively (not presented in this
paper). The height \( H_0 \) of the line connecting two points \( E \) and \( T \) is

\[
H_0 = OE \sin \theta_1 - a_0
\]

Let \( F \) be the intersecting point of \( ET \) with the line passing \( O \) and vertical
to it. We can obtain the mass between \( EF \) and that between \( TF \) from B Table
and B Graph by \( H_0 \), so the mass between \( ET \) is given by the sum or difference
of them according as \( F \) is situated between \( ET \) or on its extension.

In the case of the direct solar ray the next method is suitable. Let \( \varphi^* \) be
the sun's zenith--distance at \( T \), so we get

\[
\begin{aligned}
\cos \varphi^* &= (\cos \gamma \cos A \sin \theta_1 \cos A - \sin \theta_1 \sin A \sin \gamma \cos A \cos \theta_2) \cosh \\
&+ (\cos \gamma \cos \theta_2 - \sin \gamma \sin \theta_2 \cos A) \sinh
\end{aligned}
\]

in which \( \angle \theta_2 = \angle EOT \).

In this paper, we are considering the sun's altitude not less than 30^\circ,
which enables us to simplify the evaluation as follows: the mass traversed by
the direct ray from the upper limit of the atmosphere to the point \( T \) may be
the multiplication of the vertical mass from \( T \) to the upper limit of the
atmosphere and \( \sec \varphi^* \)

Moreover, when \( \theta = 0 \) the value of \( \gamma \) is very faintly, so we can substitute
\( \sec \varphi^* \) by \( \cosech \) in the above evaluation.

5. Numerical integration

a) Primary scattering

We have divided the line in the atmosphere into four equal parts which
pass through \( O' \) at the altitude of \( \theta = 30^\circ,60^\circ,90^\circ \), for all. Let \( E_1,E_2,E_3 \), be the
dividing points. Then \( E_0 \) is identical with \( O' \) and \( E_4 \) is on the upper limit. In
addition to these points we must adopt the auxiliary dividing points A, B, C which divide the section $E_0E_1$ into four equal parts for the line $\theta=0$ for only $\lambda=1,2,3,4$. However for $\lambda \geq 5$ only the original point $E_1, E_2, E_3$, are sufficient for this line $\theta=0$.

The evaluation has been executed for $30^\circ$-interval of $A$, between $0 \leq A \leq \pi$

b) Secondary scattering

The dividing points on the line above mentioned in the case of primary scattering are applicable for secondary one except $\theta=0$, for whose, however, the precise evaluation claims more denser division in such a way as follows:

For this line the original three points $E_1, E_2, E_3$ are sufficient for $\lambda$ larger than $\lambda=5$. However in addition to the original we must adopt the compensating points $A, B, C$ defined in the primary scattering for $\lambda=2 \sim 5$. Further in addition to the original and auxiliary points now introduced two sub-auxiliary points $A_1, A_2$ dividing the section $E_0A$ into three equal parts are indispensable for $\lambda=1$.

Next in order we must confer with the line starting from $E$ and making angle $\theta_1$ with $OE$ which must be divided into some equal parts by the dividing points denoted by $T$.

The value of $\theta_1$ of a tangent to the earth's surface is specified by $\theta_1'$ and moreover for simplicity $\frac{1}{4}(85+\theta_1')$ is denoted by $\theta_5$ and $\frac{1}{4}(90+\theta_1')$ by $\theta_8$ when $\theta_1' > 85^\circ$ in all the cases except for $E=3$ in $\theta \geq 30^\circ$; in the exceptional case of $\theta_1' < 85^\circ$, $\frac{1}{4}(80+\theta_1')$ is denoted by $\theta_5$. The notation $\theta_1''$ will be explained later. The adopted value of $\theta_1$ and the position of $T$ are given in Table 2 for each $\theta$ and $E$. In the table the last number for each $\theta_1$ gives the number of the points which are arranged in equal distance from $E$ on the section $EO''$ of the line starting from $E$ and making angle $\theta_1$ with $EO$ in which $O''$ is the intersecting point of this line and the earth's surface or the atmospheric upper limit. Therefore the point denoted by zero is identical with $E$, and the last point is $O''$ and 3 or 4 divisions are sufficient for almost all cases. But, for some other particular cases in which $EO''$ is long and so near the earth's surface that the increase of the traversed mass during the advancement of the primary scattered ray is rapid, the division must be made more dense, as seen from the Table.

In the Table the original division is denoted by the arithmetical number, the auxiliary is by the alphabetical letter and the subauxiliary is by the
letter accompanied by suffix or dash. The auxiliary points are dividing the line section bounded by the original given in the Table into \( n + 1 \) equal parts, in which \( n \) is the number of the auxiliary, and the subauxiliary points are dividing the section bounded by two auxiliary or one original and one auxiliary into \( n + 1 \) equal parts, in which \( n \) is the number of the subauxiliary.

The line starting from \( E \) and tangential to the earth's surface is divided into two sections by three points on it: \( E \), and the tangential point and the intersecting point of the upper atmospheric limit with it, the one section bounded by the former two points is characterized by \( \theta_1 \) and another section by the latter is by \( \theta_2 \).

The evaluation for the secondary scattering has been executed respectively for \( 90^\circ \) interval of \( A \) and \( A_1 \) between \( 0 \leq A \leq \pi \) and \( 0 \leq A_1 \leq 2\pi \).

6. Result of evaluation in primary scattering

The position of \( E \) in which the amount of primary scattering received at a point \( O' \) on the earth's surface from an air portion at \( E \) exposed to the direct solar ray bounded by a cone of one steradian with its axis at \( (\theta, A) \), vertex at \( O' \) and an atmospheric shell of 1m width with its centre at \( O' \) becomes maximum is always \( E = 0 \) for all combinations of \( \lambda, A, \theta \) and \( h \), showing very simple feature compared with the case \( h = 0 \). This is of course attributed to the fact that for the elevation of \( E \), in all the course of generating primary scattering, the air density is rapidly diminishing though the traversed mass is scarcely variable.

The partial wavelength domain in which the value becomes maximum for each \( E \) is constantly \( \lambda = 1 \), showing very simple feature compared with the case \( h = 0 \), for all combinations of \( h, \theta \) and \( A \) in the case \( \theta = 0 \). It may be of course attributed to the fact that the traversed mass in all the course of generation of primary scattering is small and scarcely variable for the change of \( E \) in this case of \( h \neq 0, \theta \neq 0 \). For example the mass is constant especially for the same value of \( \theta \) and \( h \) (\( \theta = h = 30^\circ \), etc.)

In the case of \( \theta = 0 \) the domain for each \( E \) is shown in Table 3, which is applicable for each \( h \) and \( A \). This Table shows that the domain moves progressively in the longer wavelength one with increase in the value of \( E \). This effect can be of course attributed to the traversed mass in all the course of the generation of primary scattering increases progressively with the distance of \( E \) from \( O' \).
Table 4 shows the primary scattering intensity received at a point on the earth's surface from an air portion bounded by a whole cone of one steradian with its axis at \((\theta, A)\) and its vertex at the point.

The value of Table 4 divided by \(k_i\) increases progressively with increase in wavelength for each \(h, \theta, A\), (the list being neglected). This value gives only the absorption effect, excluding the scattering effect, and accordingly tells us that the absorption becomes fainter with increase in wavelength.

Again, Table 4 shows that the value is maximum at \(A=0\) for each combination of \(h, \theta\) and \(\lambda\), which is attributed to the minimum of the traversed mass; and the position of \(A\) in which the value takes minimum can be given by Table 5 being applicable for each \(\lambda\).

Moreover, Table 5 shows that the position of azimuth at the minimum value of primary scattering at a point on the earth increases with increasing \(h\) and \(\theta\) throughout all the wavelength domain.

Again, Table 4 shows that the value for given \(h\) and \(A\) is maximum at \(\theta=0\) throughout all the wavelength domain and the minimum position of \(\theta\) in the same meaning is \(\theta=60^\circ\) for \(h=90^\circ\) for all \(A\) and \(\lambda\), and \(\theta=60^\circ\) or \(90^\circ\) for \(h=30^\circ\) and \(60^\circ\).

7. Result of evaluation in secondary scattering

A) The amount of secondary scattering received at a point \(O'\) on the earth's surface from an air portion at \(E\) exposed to primary scattering bounded by a cone of one steradian with its vertex at \(O'\) and axis at \((\theta, A)\) direction and a shell of \(1m\) width with its centre at \(O'\), whose primary scattering comes from an air portion at \(T\) exposed to direct solar ray bounded by a cone of one steradian with its vertex at \(E\) and axis at \((\theta_1, A_1)\) direction and a shell of \(1m\) width with its centre at \(E\), is of course nothing but the differential of (5) with respect to \(r\).

The position of \(T\), at which this amount becomes maximum is given in Table 6. The results are as follows: The increasing value of \(h\) and \(E\) makes respectively larger displacement of the position from \(E\), and the increasing of \(\theta_1\) and \(\theta\) makes closer approach to \(E\). Especially when \(\theta_1\) becomes larger enough, \(T\) is sure to coincide with \(E\), i.e., as shown in Table by zero.

B) By the numerical integration of the value of A) with respect to \(r\), we get the amount of secondary received at a point \(O'\) on the earth's surface
from an air portion at $E$ exposed to primary scattering bounded by a cone of one steradian with its vertex at $O'$ and axis at $(\theta, A)$ direction and a shell of $1m$ width with its centre at $O'$, which comes from a cone of one steradian with its vertex at $E$ and axis at $(\theta_1, A_1)$ direction. This amount is of course given by (5). We will now exhibit the detail of characteristics of this amount.

b.) The variation of the amount by $\theta_1$ for given $\lambda$.

Before proceeding to interpretation we must introduce for abridgement some notations and engagement as follows:

Let the value for $\theta_1$ be $f(\theta)$ and $f(\theta_1') + f(\theta_1'') = s$, i.e. the value for through the all tangential line to the earth from $E$ to the atmospheric upper limit, and letting $s = f(\theta_1'')$, so always $f(\theta_1''') > f(\theta_1')$. When $f(\theta_1)$ increases or decreases during the the displacement from $\theta_{1a}$ to $\theta_{1b}$, we expresses this feature by the notation $f(\theta_{1a} \sim \theta_{1b})$ or $f_d(\theta_{1a} \sim \theta_{1b})$. When the value becomes greatest at $\theta_{1a}$ during all the through domain of $\theta_1$, We expresses it by $f_g(\theta_{1a})$.

1) $\theta = 0$

The behaviour is in general case identical with that of the value of (5) divided by $\phi$ and independent of $h$ for $E = 0$, $A, B, C$, except for the particular case $A = 0$, $A_1 = \frac{\pi}{2}$, $h = 90^\circ$. Hence, we consider above two cases separately.

1) $E = 0$

The behaviour is independent of $\lambda$, and only in this case the domain of $\theta_1$ is restricted between $90^\circ \sim 180^\circ$.

a) General case

\[ f_g(90^\circ), \quad f_d(90^\circ \sim \pi). \]

b) Particular case

\[ f(90^\circ) = 0, \quad f_d(90^\circ \sim \pi), \quad f_g(\pi). \]

2) $E = A$

a) General case.

$\lambda = 1$, \quad $f(0 \sim \theta_2), \quad f_d(\theta_2 \sim \theta_1')$

Comparing the next adjacent values we get

$\lambda \geq 2$ \quad $f(\theta_2), \quad f_d(0 \sim \theta_2), \quad f_d(\theta_2 \sim \pi)$

b) Particular case

$\lambda = 1$. \quad $f_d(0 \sim \theta_1'), \quad s < f(\theta_2), \quad f(\theta_1'' \sim \theta_3)$
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\[ f_d(\theta_2 \sim 90^\circ), f(90^\circ) = 0, f(90^\circ \sim \pi), f_\theta(\pi). \]

\( \lambda = 2, 3. \) It is equal to \( \lambda = 1 \) except \( s > f(\theta_2). \)

\( \lambda \geq 4. \) It is equal to the former except \( f_d(\theta_1'' \sim 90^\circ). \) Hence, it becomes as follows:
\[ f_d(0 \sim \theta_1'), s > f(\theta_2), f_d(\theta_1'' \sim 90^\circ), f(90^\circ \sim \pi), f_\theta(\pi). \]

3) \( E = B \)

a) General case
\( \lambda = 1 \)
\[ f(0 \sim \theta_3), f_{d}(\theta_2 \sim \theta_1'), f(\theta_3) > s < f(\theta_2), f_\theta(\theta_3), f_d(\theta_2 \sim \pi). \]

\( \lambda \geq 2. \) The behaviour is the same as the case \( \lambda = 1, \) except \( s > f(\theta_3). \) Hence, it becomes as follows:
\[ f(0 \sim 62'), s > f(\theta_2), f_{d}(61' \sim 90), f(90 \sim \pi), f_\theta(\pi). \]

b) Particular case.
From \( \lambda = 1 \) to \( 4, \) it is equal to \( \lambda = 1 \) in 2), b). For \( \lambda \geq 5, \) it is equal to \( \lambda \geq 4 \) in 2), b).

4) \( E = C \)

a) General case.
\( \lambda = 1, 2. \)
\[ f(0 \sim \theta_2), f_d(\theta_2 \sim \theta_1'), f(\theta_3) > s < f(\theta_2), f_\theta(\theta_3), f_d(\theta_2 \sim \pi). \]
\( \lambda = 3. \) The behaviour is the same as the former except \( f_\theta(\theta_3). \)
\( \lambda \geq 4. \) It is identical with the former except \( s > f(\theta_3). \) Therefore, it becomes:
\[ f(0 \sim \theta_2), f_d(\theta_2 \sim \theta_1'), f(\theta_3) > s < f(\theta_2), f_\theta(\theta_3), f_d(\theta_2 \sim \pi). \]

b) Particular case.
It is identical with 3), b).

5) \( E = 1. \)

In the case of \( E \) larger than \( E = C, \) the traversed mass suffers wide variation in its value according to the value of \( A, A_1, \) so that the value now in question behaves also conspicuously, being not able to separate in only two cases as above mentioned.

a) \( A = 0, A_1 = 0, \) independently of \( h. \)
\( \lambda = 1. \)
\[ f(0 \sim \theta_1''), f_d(\theta_2 \sim \theta_1'), f(\theta_3) > s < f(\theta_2), f_\theta(\theta_3), f_d(90^\circ \sim \pi). \]
\( \lambda = 2, 3, 4. \) It is identical with
\[ f(0 \sim \theta_1''), f_d(\theta_2 \sim \theta_1'), f(\theta_3) > s < f(\theta_2), f_\theta(\theta_3), f_d(90^\circ \sim \pi). \]

b) \( A = 0, A_1 = -\frac{\pi}{2}. \)
i. \( h = 30^\circ : \)
\( \lambda = 1 \sim 4 : \)
\[ f(0 \sim \theta_1''), f_d(\theta_2 \sim \theta_1'), f(\theta_3) > s < f(\theta_2), f_\theta(\theta_3), f_d(90^\circ \sim \pi) \]
\[ \lambda \geq 5 : \quad f_\ell(0 \sim 90'), f_\ell(90'), f_\ell(90 - 7\pi). \]

ii. \( h = 60^\circ \). It is the same as \( h = 30^\circ \).

iii. \( h = 90^\circ \).

\[ \lambda = 1 \sim 3. \quad f_\ell(0 \sim \theta'), f_\ell(\theta'' \sim \theta_3), f_\ell(\theta'' \sim 90^\circ), f_\ell(90^\circ), f_\ell(90^\circ \sim \pi). \]

\[ \lambda = 4. \quad \text{It is equal to the former except} \quad f_\ell(\theta_3) < s. \]

\[ \lambda \geq 5. \quad f_\ell(0 \sim \theta_2), f_\ell(\theta_2 \sim \theta_1'), s > f_\ell(\theta_2'), f_\ell(\theta'' \sim 90^\circ), f_\ell(90^\circ), f_\ell(90^\circ \sim \pi), f_\ell(\pi). \]

c) \( A = 0, \ A_1 = \pi, \) independently of \( h \).

\[ \lambda = 1 \sim 4. \quad f_\ell(0 \sim \theta'''), f_\ell(\theta''' \sim \theta_3), f_\ell(\theta'' \sim 90^\circ), f_\ell(90^\circ), f_\ell(90^\circ \sim \pi). \]

\[ \lambda \geq 5. \quad f_\ell(0 \sim \theta'''), f_\ell(\theta''' \sim \theta_3), f_\ell(\theta'' \sim 90^\circ), f_\ell(90^\circ), f_\ell(90^\circ \sim \pi). \]

\[ d) \quad A = -\frac{\pi}{2}, \ A_1 = 0. \quad \text{It is equal to c).} \]

e) \( A = -\frac{\pi}{2}, \ A_1 = \frac{\pi}{2}. \)

i. \( h = 30^\circ : \) it is equal to \( d \).

\[ \lambda = 1 \sim 5. \quad f_\ell(0 \sim 90'), f_\ell(90'), f_\ell(90 - 7\pi). \]

\[ g) \quad A = -\frac{\pi}{2}, \ A_1 = -\frac{3}{2} - \pi. \]

i. \( h = 30^\circ : \) It is equal to \( f \).

\[ \lambda = 1 \sim 3. \quad f_\ell(0 \sim 90'), f_\ell(90'), f_\ell(90 - 7\pi). \]

\[ \lambda = 3 \sim 5. \quad f_\ell(0 \sim 90'), f_\ell(90'), f_\ell(90^\circ \sim \pi). \]

\[ \lambda \geq 6. \quad f_\ell(0 \sim 90'), f_\ell(90'), f_\ell(90^\circ \sim \pi). \]

iii. \( h = 90^\circ : \) It is equal to \( b \) iii.

\[ h) \quad A = \pi. \quad \text{It is equal to the case of the corresponding} \quad A_1, h \quad \text{and} \quad \lambda \quad \text{in} \quad A = 0 \quad \text{for each} \quad A_1, h \quad \text{and} \quad \lambda. \]

6) \( E = 2. \)

\[ a) \quad A = 0, A_1 = 0, \text{ independently of} \quad h. \]

\[ \lambda = 1 \sim 3. \quad f_\ell(0 \sim 90'), f_\ell(90'), f_\ell(90^\circ \sim \pi). \]

\[ \lambda = 3. \quad f_\ell(0 \sim \theta_3), f_\ell(\theta_3), f_\ell(\theta_3 \sim \pi). \]
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\( \lambda \geq 4 \):

\( f_s(0 \sim \theta_i'''), f_s(\theta_i''' \sim \theta_i), f_s(\theta_i'''' \sim \pi) \).

b) \( A = 0, \ A_1 = \frac{\pi}{2} \).

i. \( h = 30^\circ \):

\( \lambda = 1 \):

\( f_s(0 \sim \theta_i''), f_s(\theta_i'' \sim \theta_i), f_s(\theta_i''' \sim 90^\circ), f_s(90^\circ), f_s(90^\circ \sim \pi) \).

\( \lambda = 2 \):

\( f_s(0 \sim 90^\circ), f_s(90^\circ), f_s(90^\circ \sim \pi) \).

\( \lambda = 3 \):

\( f_s(0 \sim \theta_i), f_s(\theta_i), f_s(\theta_i \sim \pi) \).

\( \lambda \geq 4 \):

\( f_s(0 \sim \theta_i'''), f_s(\theta_i'''), f_s(\theta_i'''' \sim \pi) \).

ii. \( h = 60^\circ \):

It is equal to \( h = 30^\circ \).

ii. \( h = 90^\circ \):

\( \lambda = 1 \sim 3 \):

\( f_s(0), f_s(0 \sim \theta_i'), s < f(\theta_i), f_s(\theta_i''' \sim 90^\circ), f(90^\circ) = 0, f_s(90^\circ \sim \pi) \).

\( \lambda = 4 \). It is equal to \( \lambda = 3 \) except \( s > f(\theta_i) \).

\( \lambda = 5 \sim 9 \):

\( f_s(0 \sim \theta_i), f_s(\theta_i \sim \theta_i'''), f_s(\theta_i''' \sim 90^\circ), f(90^\circ) = 0, f_s(90^\circ \sim \pi) \).

\( \lambda = 10 \sim 12 \). It is equal to the former except the minimum at \( 85^\circ \) instead of \( \theta_i \).

c) \( A = 0, A_1 = \pi \).

i. \( h = 30^\circ \): It is equal to b), i.

\( h = 60^\circ \): It is equal to b), ii.

\( h = 90^\circ \): It is equal to \( h = 60^\circ \) in this case.

d) \( A = -\frac{\pi}{2}, A_1 = 0 \).

i. \( h = 30^\circ \): It is equal to b), i.

ii. \( h = 60^\circ \): It is equal to \( h = 30^\circ \) in this case.

iii. \( h = 90^\circ \): It is equal to a).

e) \( A = -\frac{\pi}{2}, A_1 = -\frac{\pi}{2} \).

i. \( h = 30^\circ \): It is equal to d), i.

ii. \( h = 60^\circ \):

\( \lambda = 1 \):

\( f_s(0 \sim 70^\circ), f_s(70^\circ \sim \theta_i'), s < f(\theta_i), f_s(\theta_i'''' \sim \theta_i), f_s(\theta_i \sim 90^\circ), f_s(90^\circ \sim \pi) \).

\( \lambda = 2 \):

\( f_s(0 \sim \theta_i), f_s(\theta_i), f_s(\theta_i \sim \theta_i'), s < f(\theta_i), f_s(\theta_i'''' \sim \pi) \).

\( \lambda \geq 3 \):

\( f_s(0 \sim \theta_i'''), f_s(\theta_i'''), f_s(\theta_i'''' \sim \pi) \).

iii. \( h = 90^\circ \): It is equal to b) iii.

f) \( A = -\frac{\pi}{2}, A_1 = \pi \).

i. \( h = 30^\circ \): It is equal to d), i.

ii. \( h = 60^\circ \): It is equal to d), ii.

iii. \( h = 90^\circ \): It is equal to c) iii.
\( g) \ A = \frac{\pi}{2}, \ A_1 = \frac{3}{2}\pi. \)

i. \( h = 30° \): There is no minimum.

\( \lambda = 1,2. \ f_\theta(0°-90°), f_\phi(90°), f_\sigma(90°-\pi) \)

\( \lambda = 3, \ f_\theta(0°-\theta_3), f_\phi(\theta_3), f_\sigma(\theta_3-\pi) \)

\( \lambda \geq 4. \ f_\theta(0°-\theta_3''), f_\phi(\theta_3'''), f_\sigma(\theta_3''''-\pi) \)

ii. \( h = 60° \)

\( \lambda = 1,2. \ f_\theta(0°-90°), f_\phi(90°), f_\sigma(90°-\pi) \).

\( \lambda = 3,4. \ f_\theta(0°-\theta_3), f_\phi(\theta_3), f_\sigma(\theta_3-\pi) \).

\( \lambda \geq 5. \ f_\theta(0°-\theta_3''), f_\phi(\theta_3'''), f_\sigma(\theta_3''''-\pi) \).

iii. \( h = 90° \): It is equal to \( b) \ iii. \)

\( h) \ A = \pi, \ A_1 = 0. \)

i. \( h = 30° \): It is equal to \( d) \ i. \)

ii. \( h = 60° \): It is equal to the former.

\( h = 90° \): It is equal to \( a) \).

\( i) \ A = \pi, \ A_1 = \frac{\pi}{2} \).

It is equal to \( b) \) for each \( h. \)

\( j) \ A = \pi, A_1 = \pi. \)

i. \( h = 30° \): It is equal to \( g) \ i. \)

ii. \( h = 60° \): It is equal to \( h = 30°. \)

iii. \( h = 90° \): It is equal to \( c) \ iii. \)

7) \( E = 3. \)

\( a) \ A = 0, \ A_1 = 0. \)

i. \( h = 30° \):

\( \lambda = 1,2. \ f_\theta(0°-85°), f_\phi(85°), f_\sigma(85°-\theta_3), f_\theta(\theta_3-\theta_3'''), f_\phi(\theta_3''''-\pi) \)

\( \lambda \geq 3. \) It is equal to the former except \( f_\phi(\theta_3''') \) instead of \( f_\phi(85°). \)

ii. \( h = 60° \)

\( \lambda = 1,2,3. \) It is equal to \( \lambda = 1,2 \) for \( h = 30°. \)

\( \lambda \geq 4. \) It is equal to \( \lambda \geq 3 \) for \( h = 30°. \)

iii. \( h = 90° \): It is equal to \( ii. \)

\( b) \ A = 0, \ A_1 = \frac{\pi}{2}. \)

i. \( h = 30° \): It is equal to \( a) \ i. \)

ii. \( h = 60° \): It is equal to \( a) \ ii. \)

iii. \( h = 90° \):
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\( \lambda = 1 \sim 7 \). \( f_\alpha(0 \sim \theta_1'), s' < f(\theta_2), f_\alpha(\theta_2'' \sim 90^\circ), f(90^\circ) = 0, f_\alpha(90^\circ \sim \pi) \).

\( \lambda \geq 8 \). It is equal to the former except \( s' > f(\theta_2) \) instead of \( s' < f(\theta_2) \).

c) \( A = 0, A_1 = \pi \).

It is equal to a) for each \( h \).

d) \( A = -\frac{\pi}{2}, A_1 = 0 \).

It is also equal to a) for each \( h \).

e) \( A = -\frac{\pi}{2}, A_1 = \frac{\pi}{2} \).

It is equal to d) for each \( h \).

f) \( A = -\frac{\pi}{2}, A_1 = \pi \).

It is also equal to d) for each \( h \).

g) \( A = -\frac{\pi}{2}, A_1 = \frac{3}{2}\pi \).

It is equal to d) for each \( h \).

h) \( A = \pi, A_1 = 0 \).

It is equal to a) for each \( h \).

i) \( A = \pi, A_1 = -\frac{\pi}{2} \).

It is equal to h) for each \( h \).

j) \( A = \pi, A_1 = \pi \).

It is equal to h) for each \( h \).

II ) \( \theta = 30^\circ \).

1) \( E = 0 \).

a) \( A = 0, A_1 = 0 \). Independently of \( h \) and \( \lambda \), \( f_\alpha(90^\circ), f_\alpha(90^\circ \sim \pi) \).

b) \( A = 0, A_1 = -\frac{\pi}{2} \).

It is equal to a).

c) \( A = 0, A_1 = \pi \).

It is equal to a).

d) \( A = -\frac{\pi}{2}, A_1 = 0 \).

It is equal to a).

e) \( A = -\frac{2}{\pi}, A_1 = -\frac{2}{\pi} \).

It is equal to b).

f) \( A = -\frac{\pi}{2}, A_1 = \pi \).

It is equal to c).

g) \( A = -\frac{\pi}{2}, A_1 = -\frac{3}{2}\pi \).

It is equal to b).

h) \( A = \pi, A_1 = 0 \).

It is equal to a).

i) \( A = \pi, A_1 = -\frac{\pi}{2} \).

\( h = 30^\circ \); It is equal to b).

ii. \( h = 60^\circ \); Independently of \( \lambda \), \( f(90^\circ) = 0, f_\alpha(90^\circ \sim \pi), f_\alpha(\pi) \).

iii. \( h = 90^\circ \); It is equal to b).

j) \( A = \pi, A_1 = \pi \).

It is equal to c).

2) \( E = 1 \).
a) $A = 0, A_1 = 0.$

i. $h = 30^\circ$

$\lambda = 1, 2$. $f_1(0 \sim 90^\circ), f_\phi(30^\circ), f_d(90^\circ \sim \pi).

\lambda = 3$. $f_1(0 \sim \theta_3), f_\phi(\theta_3), f_d(\theta_3 \sim \pi).

\lambda \geq 4$. $f_1(0 \sim \theta_3'''), f_\phi(\theta_3'''), f_d(\theta_3''' \sim \pi).

ii. $h = 60^\circ$

$\lambda = 1$. $f_1(0 \sim \theta_3''), f_\phi(\theta_3'' \sim \theta_3), f_d(\theta_3 \sim 90^\circ), f_\phi(90^\circ), f_d(90^\circ \sim \pi).

\lambda \geq 2$. It is equal to the corresponding $\lambda$ in i for each $h$.

iii. $h = 90^\circ$; It is equal to ii.

b) $A = 0, A_1 = \frac{\pi}{2}$. Independently of $h$, it is equal to a) ii.

c) $A = 0, A_1 = \pi$. It is equal to b).

d) $A = \frac{\pi}{2}, A_1 = 0$. It is equal to a) for each $h$.

e) $A = \frac{\pi}{2}, A_1 = \frac{\pi}{2}$.

i. $h = 30^\circ$

$\lambda = 1$. $f_1(0 \sim \theta_1''), f_\phi(\theta_1'' \sim \theta_3), f_d(\theta_3 \sim 90^\circ), f_\phi(90^\circ), f_d(90^\circ \sim \pi).

\lambda = 2$. $f_1(0 \sim 90^\circ), f_\phi(90^\circ), f_d(90^\circ \sim \pi).

\lambda \geq 3$. $f_1(0 \sim \theta_3), f_\phi(\theta_3), f_d(\theta_3 \sim \pi).

ii. $h = 60^\circ$

It is equal to i.

iii. $h = 90^\circ$; It is equal to b).

f) $A = \frac{\pi}{2}, A_1 = \pi$.

i. $h = 30^\circ$; It is equal to d).

ii. $h = 60^\circ$

$\lambda = 1$. $f_1(0 \sim \theta_1'''), f_\phi(\theta_1'''' \sim \theta_3), f_d(\theta_3 \sim 90^\circ), f_\phi(90^\circ), f_d(90^\circ \sim \pi).

\lambda \geq 2$. It is equal to i.

iii. $h = 90^\circ$; It is equal to c).

g) $A = \frac{\pi}{2}, A_1 = \frac{3}{2} \pi$. It is equal to f).

h) $A = \pi, A_1 = 0$.

i. $h = 30^\circ$

$\lambda = 1$. $f_1(0 \sim \theta_1'''), f_\phi(\theta_1'''' \sim \theta_3), f_d(\theta_3 \sim 90^\circ), f_\phi(90^\circ), f_d(90^\circ \sim \pi).

\lambda = 2$. $f_1(0 \sim 90^\circ), f_\phi(90^\circ), f_d(90^\circ \sim \pi).

\lambda = 3$. $f_1(0 \sim \theta_3), f_\phi(\theta_3), f_d(\theta_3 \sim \pi).

\lambda \geq 4$. $f_1(0 \sim \theta_3'''), f_\phi(\theta_3''''), f_d(\theta_3''' \sim \pi).
ii. \( h = 60^\circ \);
\[ \lambda = 1 \quad \Rightarrow f(0 \sim 85^\circ), \quad f_\theta(85^\circ \sim \theta_3), \quad f_\theta(\theta_2 \sim \theta_1''), \quad f_\theta(\theta_1'' \sim 90^\circ), \quad f_\theta(90^\circ), \quad f_\theta(90^\circ \sim \pi) . \]
\[ \lambda = 2 \quad \Rightarrow f_\theta(0 \sim \theta_2), \quad f_\theta(\theta_3 \sim \theta_1''), \quad f_\theta(\theta_1'' \sim 90^\circ), \quad f_\theta(90^\circ) = 0 , \]
\[ f_\theta(90^\circ \sim \pi) . \]

iii. \( h = 90^\circ \); It is equal to i).

i) \( A = \pi, A_1 = \frac{\pi}{2} . \)

ii. \( h = 30^\circ \); It is equal to b).

ii. \( h = 60^\circ \);
\[ \lambda = 1 \sim 4 \quad \Rightarrow f_\theta(0), \quad f_\theta(0 \sim \theta_1'), \quad f_\theta(\theta_1'' \sim 90^\circ), \quad f_\theta(90^\circ), \quad f_\theta(90^\circ \sim \pi) . \]
\[ \lambda \geq 5 \quad \Rightarrow f_\theta(0), \quad f_\theta(0 \sim \theta_3), \quad f_\theta(\theta_2 \sim \theta_1''), \quad f_\theta(\theta_1'' \sim 90^\circ), \quad f_\theta(90^\circ) = 0 , \]
\[ f_\theta(90^\circ \sim \pi) . \]

iii. \( h = 90^\circ \); It is equal to b).

j) \( A = \pi, A_1 = \pi . \)

i. \( h = 30^\circ \); It is equal to h).

ii. \( h = 60^\circ \); It is equal to i).

iii. \( h = 90^\circ \); It is equal to c).

3) \( E = 2 . \)

a) \( A = 0, A_1 = 0 . \) Independently of \( h , \)
\[ \lambda = 1 \quad \Rightarrow f_\theta(0 \sim 85^\circ), \quad f_\theta(85^\circ), \quad f_\theta(85^\circ \sim \pi) . \]
\[ \lambda = 2 \quad \Rightarrow f_\theta(0 \sim \theta_2), \quad f_\theta(\theta_3), \quad f_\theta(\theta_2 \sim \theta_1'), \quad f_\theta(\theta_1' \sim \pi) . \]

In both \( \lambda , \) \( f(\theta_1'') = 0 , \) then \( s = f(\theta_1') . \)
\[ \lambda \geq 3 \quad \Rightarrow f_\theta(0 \sim \theta_1''), \quad f_\theta(\theta_1''), \quad f_\theta(\theta_1'' \sim \pi) . \]

b) \( A = 0, A_1 = \frac{\pi}{2} . \) It is equal to a).

c) \( A = 0, A_1 = \pi . \) It is equal to a).

d) \( A = \frac{\pi}{2}, A_1 = 0 . \) Independently of \( h , \) it is equal to a).

e) \( A = \frac{\pi}{2}, A_1 = \frac{\pi}{2} . \) It is equal to d).

f) \( A = \frac{\pi}{2}, A_1 = \pi . \) It is equal to d).

g) \( A = \frac{\pi}{2}, A_1 = \frac{3}{2} - \pi . \) It is equal to d).

h) \( A = \pi, A_1 = 0 . \) It is equal to a).

i) \( A = \pi, A_1 = \frac{\pi}{2} . \)

i. \( h = 30^\circ \); It is equal to the former.
ii. $h=60^\circ$ ;
\begin{align*}
\lambda &= 1, 2, 3. \text{ It is equal to the case of } \lambda = 1 \sim 4 \text{ in 2) i), ii.} \\
\lambda &= 4. \text{ It is equal to the case of } \lambda = 5 \text{ in 2), i), ii.} \\
\lambda &\geq 5. \quad f_P(0), f_a(0 \sim 85^\circ), f_a(85^\circ \sim \theta_1''), f_a(\theta_1'' \sim 90^\circ), f(90^\circ) = 0, f(90^\circ \sim \pi).
\end{align*}

iii. $h=90^\circ$ ; It is equal to b).

j) $A = \pi, A_1 = \pi$. It is equal to a) for all $h$.

4) $E = 3$.

a) $A = 0, A_1 = 0$.

i. $h=30^\circ$ ;
\begin{align*}
\lambda &= 1 \sim 5. \quad f_P(0 \sim 85^\circ), f_a(85^\circ), f_a(85^\circ \sim \pi). \\
\lambda &\geq 6. \quad f_P(0 \sim \theta_1'''), f_a(\theta_1'''), f_a(\theta_1''' \sim \pi).
\end{align*}

ii. $h=60^\circ$ ; It is equal to i.

iii. $h=90^\circ$ ;
\begin{align*}
\lambda &= 1. \quad f_P(0 \sim \theta_1'''), f_a(\theta_1'''), f_a(\theta_1''' \sim \pi). \\
\lambda &= 2, 3, 4. \quad f_P(0 \sim 85^\circ), f_a(85^\circ), f_a(85^\circ \sim \pi). \\
\lambda &\geq 5. \text{ It is equal to } \lambda = 1.
\end{align*}

The behaviour of a) can be applied to b), c), ........ and h) (i.e. $A = \pi, A_1 = 0$) for each $h$.

i) $A = \pi, A_1 = \frac{\pi}{2}$.

i. $h=30^\circ$ : It is equal to a) i.

ii. $h=60^\circ$ :
\begin{align*}
\lambda &= 1, 2, 3. \quad f_P(0), f_a(0 \sim \theta_1'), f_a(\theta_1' \sim 85^\circ), f_a(85^\circ \sim 90^\circ), f(90^\circ) = 0, \\
&\quad f(90^\circ \sim \pi), \text{ here } f(\theta_1') \text{ is negligibly small, then } s = f(\theta_1'). \\
\lambda &\geq 4. \quad f_P(0), f_a(0 \sim \theta_2), f_a(\theta_2 \sim 85^\circ), f_a(85^\circ \sim 90^\circ), f(90^\circ) = 0, f(90^\circ \sim \pi).
\end{align*}

j) $A = \pi, A_1 = \pi$. It is equal to a) for each $h$.

\[ \lambda = 60^\circ. \]

1) $E = 0$.

With only one exception, $f_P(90^\circ), f_a(90^\circ \sim \pi)$, for any combination of $A, A_1, h, \lambda$.

For $A = \pi, A_1 = \frac{\pi}{2}, h=60^\circ$: $f(90^\circ) = 0, f(90^\circ \sim \pi), f(\pi)$, for each $\lambda$.

2) $E = 1$.

With only one exception, it behaves as follows:
\begin{align*}
\lambda &= 1. \quad f_a(0 \sim \theta_1'''), f_a(\theta_1''' \sim \theta_3), f_a(\theta_3 \sim 90^\circ), f_p(90^\circ), f_a(90^\circ \sim \pi).
\end{align*}
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$\lambda = 2$. $f_\ell(0 \sim 90^\circ), f_\rho(90^\circ), f_d(90^\circ \sim \pi)$.

$\lambda = 3$. $f_\ell(0 \sim \theta_2), f_\rho(\theta_2), f_d(\theta_2 \sim \pi)$.

$\lambda \geq 4$. $f_\ell(0 \sim \theta_1''''), f_\rho(\theta_1'''), f_d(\theta_1'''' \sim \pi)$.

One exception is the case $A = \pi, A_1 = \frac{\pi}{2}, h = 30^\circ$. In this case, it is the same as the case $\theta = 30^\circ, E = 1, A = \pi, A_1 = \frac{\pi}{2}, h = 60^\circ$.

3) $E = 2$.

i. $h = 30^\circ$: With only one exception, it behaves as follows for all combination of $A, A_1$.

$\lambda = 1$. $f_\ell(0 \sim 85^\circ), f_\rho(85^\circ), f_d(85^\circ \sim \theta_2), f_d(\theta_2 \sim \theta_1''''), f_d(\theta_1'''' \sim \pi)$.

$\lambda = 2$. $f_\ell(0 \sim 85^\circ), f_\rho(85^\circ), f_d(85^\circ \sim \pi)$.

$\lambda \geq 3$. $f_\ell(0 \sim \theta_1''''), f_\rho(\theta_1''''), f_d(\theta_1'''' \sim \pi)$.

The exception occurs in $A = \pi, A_1 = \frac{\pi}{2}$, whose case behaves in the same way as $\theta = 30^\circ, E = 2, A = \pi, A_1 = \frac{\pi}{2}, h = 60^\circ$.

ii. $h = 60^\circ$: With no exception it behaves as follows for all combination of $A, A_1$.

$\lambda = 1, 2$. $f_\ell(0 \sim 85^\circ), f_\rho(85^\circ), f_d(85^\circ \sim \pi)$.

$\lambda \geq 3$. $f_\ell(0 \sim \theta_1''''), f_\rho(\theta_1''''), f_d(\theta_1'''' \sim \pi)$.

iii. $h = 90^\circ$: It is equal to ii.

4) $E = 3$.

With only one exception it behaves as follows for any combination of $A, A_1, h$.

$\lambda = 1 \sim 5$. $f_\ell(0 \sim 85^\circ), f_\rho(85^\circ), f_d(85^\circ \sim \pi)$.

$\lambda \geq 6$. $f_\ell(0 \sim \theta_1''''), f_\rho(\theta_1''''), f_d(\theta_1'''' \sim \pi)$.

One exception is $A = \pi, A_1 = \frac{\pi}{2}, h = 30^\circ$, in which it behaves in the same way as $\theta = 30^\circ, E = 3, A = \pi, A_1 = \frac{\pi}{2}, h = 60$.

IV) $\theta = 90^\circ$.

1) $E = 0$.

For any combination of $A, A_1, h, \lambda$, $f_\rho(90^\circ), f_d(90^\circ \sim \pi)$.

2) $E = 1$.

i. $h = 30^\circ$: For any combination of $A, A_1$,

$\lambda = 1, 2$. $f_\ell(0 \sim 90^\circ), f_\rho(90^\circ), f_d(90^\circ \sim \pi)$.
\[ \lambda = 3. \quad f_{\theta}(0 \sim \theta_3), \quad f_{\phi}(\theta_3), \quad f_{a}(\theta_3 \sim \pi). \]
\[ \lambda \geq 4. \quad f_{\theta}(0 \sim \theta_1'), \quad f_{\phi}(\theta_1'), \quad f_{a}(\theta_1' \sim \pi). \]

ii. \( h=60^\circ \): For all combination of \( A, A_1 \).
\[ \lambda = 1. \quad f_{\theta}(0 \sim \theta_1''), \quad f_{\phi}(\theta_1'' \sim \theta_3), \quad f_{d}(\theta_3 \sim 90^\circ), \quad f_{a}(90^\circ \sim \pi). \]
\[ \lambda = 2. \quad f_{\theta}(0 \sim 90^\circ), \quad f_{\phi}(90^\circ), \quad f_{a}(90^\circ \sim \pi). \]
\[ \lambda = 3. \quad f_{\theta}(0 \sim \theta_3), \quad f_{\phi}(\theta_3), \quad f_{a}(\theta_3 \sim \pi). \]
\[ \lambda \geq 4. \quad f_{\theta}(0 \sim \theta_1''), \quad f_{\phi}(\theta_1''), \quad f_{a}(\theta_1'' \sim \pi). \]

iii. \( h=90^\circ \): It is equal to ii .

3 ) \( E=2 \).

For all combination of \( A, A_1, h, \lambda \), with no exception, \( f_{\theta}(0 \sim \theta_1''), \quad f_{\phi}(\theta_1''), \quad f_{a}(\theta_1'' \sim \pi). \)

4 ) \( E=3 \).

For all combination of \( A, A_1, h \) with no exception it follows :
\[ \lambda = 1 \sim 5. \quad f_{\theta}(0 \sim 85^\circ), \quad f_{\phi}(85^\circ), \quad f_{a}(85^\circ \sim \pi). \]
\[ \lambda \geq 6. \quad f_{\theta}(0 \sim \theta_1''), \quad f_{\phi}(\theta_1''), \quad f_{a}(\theta_1'' \sim \pi). \]

Eventually, throughout all \( \theta \) for the shorter wavelength, especially in \( \lambda =1 \), the behaviour, having one or two minimums, is considerably complex comparing with the longer one presumably because the former is very sensible for the amount of the traversed mass.

Moreover, that the behaviour exhibits slighter correlation to \( A, A_1 \) with increasing value of \( \theta \) among \( \theta =30^\circ \sim 90^\circ \) may be readily reduced to the fact that both the value of \( \phi \) (the polarization angle) and the traversed mass are progressively less affected by \( A, A_1 \) with its increasing.

b.) The variation of the amount by \( \lambda \) for given \( \theta_1 \).

It has been found that the feature has no minimum and moreover is indifferent to \( A \) and \( A_1 \) for \( h \geq 30^\circ \). These two make jointly the discussion much simpler.

Table 7 shows the value of \( \lambda \) in which the amount becomes maximum for given \( \theta, E, h \) and \( \theta_1 \).

According to the Table: The longer traversed mass displaces the maximum to the longer wavelength, i.e., it increases with increase in \( E \).

With increase in \( \theta \) from 0° to 90°, the traversed mass decreases, which makes closer approach of the maximum to the shorter wavelength. The amount decreases monotonously with the distance from only one existing maximum.
Intensity of Scattered Light for each Wavelength to the Sky Light at Daytime

position.

c) By the numerical integration of (5) with respect to \( A_1 \) and \( \theta_1 \) we get the secondary scattering received at a point \( O' \) on the earth's surface from an air portion at \( E \) bounded by a cone of one steradian with its vertex at \( O' \) and axis at \((\theta, A)\) direction and a shell of 1m width with its centre at \( O' \), which is exposed to primary scattering from all directions.

c_1) The position of \( E \) at which the amount becomes maximum for given \( \lambda \) is shown in Table 8 which is indifferent to \( A \) and \( h \).

The position makes closer approach to \( O' \) with increase in \( \theta \) and \( \lambda \), considering that we have not used the sub-auxiliary points \( A_1, A_2 \) for \( \lambda \leq 3, 4, 5 \). If we will adopt the points the position would take maximum value at \( A_1 \) or \( A_2 \) in these \( \lambda \).

c_2) The position of \( \lambda \) at which the amount becomes maximum for given \( E \) is shown in Table 9, which is indifferent to \( h \) and \( A \).

Although we cannot recognize the dependency of \( \lambda \) to \( \theta \) owing to the rough step of \( \theta \), we may conclude that the maximum \( \lambda \) walks to the longer wavelength with increase in \( E \).

D) By the numerical integration of the amount given in C) with respect to \( E \) we get the amount of secondary scattering received at a point \( O' \) on the earth's surface from a whole cone of one steradian with its vertex at \( O' \) and axis at \((\theta, A)\) direction, as shown in Table 10.

This Table shows that: the value takes max. at \( A = 0 \) indifferent to \( h \) and \( \theta \), but the azimuth of mini. value comes in gradually opposite the sun with increase in \( \theta, h \) and \( \lambda \). The value for given \( h \) and \( A \) is max. at \( \theta = 0 \) for each \( \lambda \).

The value is in general speaking predominant in \( h = 60^\circ \) comparing with the same \( \theta \) and \( A \).

By making the ratio of secondary : primary by Table 4 and 10, we can conclude: The ratio increases with increase in respectively \( \theta \) and \( A \) for each \( h \) and \( \lambda \), as well as with increase in respectively \( h \) and \( A \) for each \( \theta \) and \( \lambda \).

The maximum ratio is generally inclined to make occurrence at \( A = 90^\circ \) with increase in \( \lambda \). Moreover the ratio becomes smaller i.e. the secondary intensity becomes less predominant with larger \( \theta \) for each \( h, \lambda \) and \( A \).

E) By the numerical integration of the amount of (D) with respect to \( A \) and \( \theta \), we get the horizontal intensity of secondary scattering received at a
point $O'$ on the earth's surface, as shown in Table 11 (c), accompanied by the value for $h=0$ given in Ref. (3). In the same way as above we can get the value for primary scattering from Table 4 as shown in Table 11 (b).

According to Table 11 (b) we can conclude: in the horizontal primary scattering intensity, primary scattering intensity takes maximum value for each $\lambda$ is always $h=90^\circ$, but as for the secondary it decreases with the increase of $\lambda$ and for the total wavelength domain it occurs at $h=90^\circ$, as shown in Table 11 (c) and 12.

The ratio of the secondary to the primary scattering with respect to the horizontal intensity is given in Table 13, which shows that: The ratio decreases with the increase of both $h$ and $\lambda$, which may be a distinguished feature. However, with respect to the total domain, it becomes maximum at $h=30^\circ$ instead of $h=0^\circ$, which deserves much attention. The ratio of primary to direct solar ray in the same meaning has the same correspondence to $h$ and $\lambda$ as the former ratio as shown in Table 14 except the total domain.

8. Comparison with other researches

As the sky radiation $H_s^{(1)}$ corresponding to the primary scattering is not given but the ratio $H_s^{(1)}/H_s$ and $H_s$ are given in Ref. (4), Sato has computed $H_s^{(1)}$ by multiplying $H_s$ by $H_s^{(1)}/H_s$. The result is shown in Table 15 (a). He has computed also the difference of $H_s$ given by Sekera and $H_s^{(1)}$ given in (a), as shown in (b) in the table. Comparing the relative sun radiation in Table 1 in 383p of l.c., (a) and (b) above mentioned respectively with Tables 11 (a), (b) and (c) given by Sato, we can find the same variation of the amount as functions of wavelength and zenith distance, that is to say, the relative horizontal intensity corresponding to primary scattering decreases with increasing wavelength and zenith distance, while, corresponding to higher order scatterings decreases with increasing wavelength, but is not unique to zenith distance. Here we must add the next caution: To the above comparison it is indispensable to use the exact wavelength $\lambda_i'$ corresponding to $k_i$ instead of the mean wavelength $\lambda_{\text{m}}$ in each domain which is given in Table 1.

The horizontal global radiation $G_s$ means $H_s+S_s$ by Sekera's notation. The integrated relative horizontal global radiation for the whole range of wavelength is given by the sum of three values given in the last column of Table 11, (a),
(b), (c) at each altitude, i.e.,

\[ h = 0 \quad 30 \quad 60 \quad 90 \]
\[ 0.0060 \quad 0.457 \quad 0.820 \quad 0.954 \]

The corresponding value of Sekera can be given by \( G_0 \) in Table 6 in l.c. divided by 1390.55, which gives

\[ z = 0 \quad 53.1 \quad 84.3 \quad 88.8 \]
\[ 0.957 \quad 0.561 \quad 0.080 \quad 0.013 \]

The author has found that both representations are in good coincidence by the graphical expression.

The distribution of the sky radiation for the whole range of wavelength in the sky dome is observed by Dorno (Ref.5).

The theoretical result can be given by the sum of the values of the last columns "total" in Table 4 and 10 for each \( h, \theta \) and \( A \), which is given in Table 16. Here the value for \( h=0 \) is given by the same method from Tables 6 and 13 in Ref. (3). We can conclude from the table:

1) The radiation is likely to increase with decreasing \( \theta \) for any \( A \), taking the greatest value at horizon.

2) The smallest value occurs at \( A=\pi, \theta = \frac{\pi}{2} - h \) at the sun's low altitude, though at higher altitude this is perturbed by (1).

3) The radiation has the partial maximum but not absolute maximum by the perturbation of the fact (1) near the sun.

Dorno's observation agrees with the theory in (1) and (2), but he observes absolute maximum near the sun, which is contrary to (1). This only one existing opposition between them would be attributed to two reasons: Dorno would have probably observed jointly the sky radiation and the sun's partial radiation near the sun. The sky radiation in this place would be generated not only by the Rayleigh scattering but also by the reflection and refraction of ice crystals as Wiener says (Ref. 6).

In conclusion, it would be remarkable that we can discover too little difference between the author's and Sekara's results and Dorno's observation.

References


3) Sato, T. (1961): The contribution of the intensity in scattered light of each wavelength to the sky light at sunrise and sunset. ibid., 39, 116-133.


Table 1. Values of $\lambda_i$ (wavelength at the boundary of each domain), $\rho_t$ (transmission coefficient for each domain) and $k_t$ (its extinction coefficient).

<table>
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<tr>
<th>$\lambda$</th>
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<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>0.409$\mu$</td>
<td>0.466</td>
<td>0.519</td>
<td>0.577</td>
<td>0.638</td>
<td>0.708</td>
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<td>0.941</td>
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<tr>
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<td>0.221-10$^{-3}$</td>
<td>0.139-10$^{-3}$</td>
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<td>0.0836-10$^{-4}$</td>
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<td>0.493</td>
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<td>0.607</td>
<td>0.673</td>
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<td>$\lambda'$</td>
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</table>

Table 3. Position of the partial wavelength domain, in which the value of primary scattering received at a point $O'$ on the earth's surface from an air portion exposed to the direct solar ray with its centre at $E$ bounded by a cone of one steradian with its axis at $(\theta, \lambda)$ direction and an atmospheric shell of 1 m width with its centre at $O'$ becomes maximum for each $E$ on the line $\theta=0$, being applicable to all $h$ and $\lambda$.

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<tr>
<th>$E$</th>
<th>0</th>
<th>A</th>
<th>B</th>
<th>C</th>
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<th>3</th>
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Table 5. Position of azimuth $\lambda$ in which the value of Table 4 becomes minimum, being applicable for each $\lambda$.

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<tr>
<td>h 90$^\circ$</td>
<td>120$^\circ$</td>
<td>180$^\circ$</td>
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<tr>
<td>h 60$^\circ$</td>
<td>90$^\circ$</td>
<td>180$^\circ$</td>
<td>180$^\circ$</td>
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Table 2. Number and positions of T point on the line section passing E point and with $\theta_1$ direction.

<table>
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<tr>
<th>$\theta$</th>
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<tr>
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$E_1$ for each of $A_1 A_2 A B C$

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Intensity of Scattered Light for each Wavelength to the Sky Light at Daytime
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Table 6. The position of $T$, at which the following amount becomes maximum: Secondary scattering received at a point $O'$ on the earth's surface from an air portion at $E$ exposed to primary scattering bounded by a cone of one steradian with its vertex at $O'$ and axis at $(\theta, A)$ direction and a shell of 1 m width with its centre at $O'$, whose primary scattering comes from an air portion at $T$ exposed to direct solar ray bounded by a cone of one steradian with its vertex at $E$ and axis at $(\theta, A)$ direction and a shell of 1 m width with its centre at $E$. The value for $E=0$ is not listed in the Table as it is always zero, i.e., in this case the position of $T$ coincides with $E$, for each $\theta$ and $\lambda$.

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Intensity of Scattered Light for each Wavelength to the Sky Light at Daytime

89
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Table 6. Continued.
Table 6. Continued.

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Intensity of Scattered Light for each Wavelength to the Sky Light at Daytime.
Table 7. The value of $I$ in which the amount computed from eq. (5) becomes maximum for given $\theta$, $E$, $h$, and $\theta_1$.

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Table 8. The position of $E$ at which the next amount becomes maximum for given $\lambda$: The secondary scattering received at a point $O'$ on the earth's surface from an air portion at $E$ bounded by a cone of one steradian with its vertex at $O'$ and axis at $(\theta, A)$ direction and a shell of 1 m width with its centre at $O'$, which is exposed to primary scattering from all directions.

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Table 9. The position of $\lambda$ at which the amount in the same meaning as Table 8 becomes maximum for given $E$, independent of $h$ and $A$. 

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Table 10. The amount of secondary scattering received at a point $O'$ on the earth's surface from a whole cone of one steradian with its vertex at $O'$ and axis at $(\theta, A)$ direction, in the same unit as in Table 4.

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Total $10^{-4}$
Table 11. The horizontal intensity of direct solar ray (a), primary scattering (b), secondary scattering (c) received at a point $O'$ on the earth's surface, in the same unit as in Table 4.

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<td>61</td>
<td>195</td>
<td>227</td>
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</tr>
</tbody>
</table>

Table 12. The sun's altitude at which the horizontal secondary scattering intensity takes maximum value for each $\lambda$.

<table>
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<tr>
<th>$\lambda$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>60</td>
<td>30</td>
<td>30</td>
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<td>30</td>
<td>30</td>
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<td>90</td>
</tr>
</tbody>
</table>

Table 13. The amount of the ratio of secondary to primary scattering with respect to the horizontal intensity.

<table>
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<tr>
<th>$\lambda$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$</td>
<td>0</td>
<td>0.532</td>
<td>0.279</td>
<td>0.195</td>
<td>0.138</td>
<td>0.100</td>
<td>0.071</td>
<td>0.051</td>
<td>0.031</td>
<td>0.019</td>
<td>0.011</td>
<td>0.363</td>
<td>0.463</td>
</tr>
<tr>
<td>30</td>
<td>0.441</td>
<td>0.260</td>
<td>0.186</td>
<td>0.138</td>
<td>0.099</td>
<td>0.070</td>
<td>0.050</td>
<td>0.030</td>
<td>0.018</td>
<td>0.0104</td>
<td>0.361</td>
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</tr>
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<td>0.244</td>
<td>0.175</td>
<td>0.127</td>
<td>0.091</td>
<td>0.064</td>
<td>0.046</td>
<td>0.028</td>
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<td>0.0095</td>
<td>0.329</td>
<td>0.402</td>
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<tr>
<td>90</td>
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<td>0.235</td>
<td>0.169</td>
<td>0.122</td>
<td>0.087</td>
<td>0.061</td>
<td>0.044</td>
<td>0.027</td>
<td>0.016</td>
<td>0.0090</td>
<td>0.312</td>
<td>0.381</td>
<td>0.233</td>
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</table>
Intensity of Scattered Light for each Wavelength to the Sky Light at Daytime

Table 14. The amount of the ratio of primary scattering to direct solar ray in the same meaning as Table 12.

<table>
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<tr>
<th>( \lambda )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
<td>10^{-2}</td>
</tr>
<tr>
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<td>0.119</td>
<td>0.076</td>
<td>0.050</td>
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<td>0.022</td>
<td>1.25</td>
<td>0.717</td>
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<td>0.163</td>
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</tr>
<tr>
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<td>0.069</td>
<td>0.045</td>
<td>0.030</td>
<td>0.019</td>
<td>0.013</td>
<td>0.757</td>
<td>0.436</td>
<td>0.244</td>
<td>0.099</td>
<td>0.099</td>
<td>0.035</td>
</tr>
<tr>
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<td>0.197</td>
<td>0.095</td>
<td>0.060</td>
<td>0.040</td>
<td>0.026</td>
<td>0.017</td>
<td>0.012</td>
<td>0.673</td>
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<td>0.089</td>
<td>0.089</td>
<td>0.032</td>
</tr>
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</table>

Table 15. The horizontal sky radiation corresponding to primary scattering (a) and that corresponding to all of higher orders scattering (b), computed by Sato from Sekera's results, Z being solar zenith distance.

<table>
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<th>( \lambda )</th>
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<th>0.436</th>
<th>0.495</th>
<th>0.618</th>
<th>0.809</th>
<th>1.000</th>
<th>1.500</th>
<th>2.000</th>
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</thead>
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<td>0.0805</td>
<td>0.0564</td>
<td>0.0263</td>
<td>0.0095</td>
<td>0.0042</td>
<td>0.0008</td>
<td>0.0003</td>
</tr>
<tr>
<td>53,1</td>
<td>0.0745</td>
<td>0.0703</td>
<td>0.0517</td>
<td>0.0253</td>
<td>0.0094</td>
<td>0.0042</td>
<td>0.0008</td>
<td>0.0003</td>
</tr>
<tr>
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<td>0.0824</td>
<td>0.0196</td>
<td>0.0086</td>
<td>0.0040</td>
<td>0.0008</td>
<td>0.0003</td>
</tr>
<tr>
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<td>0.0060</td>
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<table>
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<th>0.0131</th>
<th>0.0028</th>
<th>0.00040</th>
<th>0.00009</th>
<th>0.4\times10^{-5}</th>
<th>0.0000</th>
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<td>0.0027</td>
<td>0.00045</td>
<td>0.00012</td>
<td>0.8\times10^{-5}</td>
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<tr>
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<td>0.0011</td>
<td>0.00031</td>
<td>0.00010</td>
<td>0.8\times10^{-5}</td>
<td>0.0000</td>
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Table 16. The amount of the sky radiation corresponding to primary and secondary scattering in the same unit as the last column "total" in Tables 4 and 10.

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<th>90</th>
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<th>60</th>
<th>90</th>
<th>0</th>
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<th>60</th>
<th>90</th>
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</thead>
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<td>10^{-5}</td>
<td>10^{-5}</td>
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<td>10^{-4}</td>
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