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Observing the Sun and Moon during a Lunar Eclipse

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SUMMARY

Because of the size of the Earth's umbral cone at the Moon's distance, there will be locations where both the Sun and the Moon are above the visible horizon during the partial phase and the beginning and end of totality of a lunar eclipse. Observers at these locations are provided with the rare opportunity of simultaneously seeing all three bodies participating in the eclipse. Near these locations it should also be possible to observe the Earth's shadow projected first on the atmosphere as the twilight wedge and then on the surface of the Moon. Optimal locations for such observations are given for all eclipses in the years 1996–2015.

1 INTRODUCTION

A solar eclipse presents a unique spectacle to an observer fortunate enough to be stationed in the path of totality. In the partial phases, all three bodies, the Earth, Sun and Moon, participating in the eclipse are visible and the spatial geometry of the event is readily appreciated. In contrast, during a lunar eclipse the Sun is well below the observer's horizon and thus only two of the participating bodies can be seen. One fascinating occurrence during a solar eclipse is the passage of the umbral cone. At that moment, the shadow of the Moon seems to drop from the sky. During totality the bright horizon can be seen beyond the shadow edge, which is never located more than 100 km from the observer. Regions in and out of the Moon's shadow are then easily distinguished. For a lunar eclipse the umbral cone is not normally experienced directly, but is seen at a distance projected on the surface of the Moon. In this article it is shown that, by a judicious choice of location, it should be possible to observe the Earth, Sun and Moon simultaneously during a lunar eclipse or to experience the Earth's umbral cone both locally and projected onto the Moon's surface.

At the beginning and end of the partial phase of a lunar eclipse (first and fourth contacts), the centre of the Moon and that of the Earth's shadow, i.e. the point diametrically opposite the Sun, are separated by (1)

$$\Delta_{1,4} = 1{\cdot}02(\pi_\odot + 0{\cdot}998\,33\,\pi_m - \theta_\odot) + \theta_m, \tag{1}$$

where $\pi_\odot$ and π_m are the equatorial horizontal parallaxes of the Sun and the Moon, respectively, and $\theta_\odot$, θ_m are their geocentric angular semidiameters. The factor 1·02 is conventionally used to take account of the effect of refraction by the Earth's atmosphere, and 0·99833 is a correction for the

Earth's mean oblateness. At the beginning and end of totality (second and third contacts) the separation is

$$\Delta_{2,3} = 1{\cdot}02(\pi_\odot + 0{\cdot}998\,33\pi_m - \theta_\odot) - \theta_m. \quad (2)$$

$\Delta_{1,4}$ varies from 1° 03′·5 to 53′·2, and $\Delta_{2,3}$ from 30′·0 to 23′·8. There must therefore be locations where the Sun and the Moon are both still above the horizon during the partial and at least part of the total phases of a lunar eclipse. In that case all three participating bodies would be visible in principle. It is clear that at the locations where such observations could be made, the eclipse would begin around sunset or end around sunrise. The visibility of the totally eclipsed Moon depends on its brightness, and this is rather difficult to predict. For observers stationed where the partial phases begin just after sunset or end after sunrise it should be possible to see the Earth's shadow as the well-known 'twilight wedge' first projected on the atmosphere and then on the Moon's surface. Conditions for both types of observation would be improved from high-flying aircraft, first because horizon dip would raise the Moon further above the horizon, and second because the edge of the twilight wedge remains sharply defined higher above the horizon. For an explanation of this last phenomenon see, for example, Greenler (**2**, p. 131).

In this paper we show how to calculate the locations where the lower limb of the Sun would be on the horizon and the Moon would be at its maximum possible altitude. These optimum locations are listed for the contact times and for altitudes from 0 to 40000 ft of all partial and total eclipses up to and including the year 2015.

2 CALCULATION OF OPTIMAL LOCATIONS

Let $\mathbf{r}_\odot$ and $\mathbf{r}_m$ be unit vectors representing the positions of the Sun and the Moon obtained from their right ascension, α, and declination, δ, by the relation

$$\mathbf{r} = (\cos\alpha\cos\delta, \sin\alpha\cos\delta, \sin\delta). \quad (3)$$

Using '·' and '×' to denote the scalar and vector cross-products, we see that the unit vector

$$\mathbf{r}_0 = \frac{(\mathbf{r}_\odot \times \mathbf{r}_m) \times \mathbf{r}_\odot}{|\mathbf{r}_\odot \times \mathbf{r}_m|} \quad (4)$$

$$= \frac{\mathbf{r}_m - (\mathbf{r}_\odot \cdot \mathbf{r}_m)\mathbf{r}_\odot}{\sqrt{[1 + (\mathbf{r}_\odot \cdot \mathbf{r}_m)^2]}} \quad (5)$$

is orthogonal to $\mathbf{r}_\odot$ and lies in the same plane as $\mathbf{r}_\odot$ and $\mathbf{r}_m$. Any unit vector lying in this plane can then be written as

$$\mathbf{v} \equiv (v_x, v_y, v_z) = \mathbf{r}_0 \sin\theta + \mathbf{r}_\odot \cos\theta, \quad (6)$$

where θ is the angle between $\mathbf{r}_\odot$ and $\mathbf{v}$.

We seek locations to maximize the visibility of the Sun and the Moon at the beginnings and ends of the partial phases and total phases of the lunar eclipse. To do this we require that the lower limb of the Sun sit on the observer's visible horizon, taking into account the effects of horizon dip and atmospheric refraction. The zenithal distance of the Sun, $z_{\odot}$, can thereby be fixed. The zenithal point at the location where the altitude of the Moon is maximum will lie in the same plane as $\mathbf{r}_{\odot}$ and $\mathbf{r}_{\mathrm{m}}$ and can thus be obtained by setting $\theta = z_{\odot}$ in equation (6). The longitude, λ_{opt}, and latitude, ϕ_{opt}, of the optimal observation point can then be obtained from the components of $\mathbf{v}$ via the relations

$$\tan(\lambda_{\mathrm{opt}} + \mathrm{GHA}) = \frac{v_y}{v_x}, \tag{7}$$

$$\sin\phi_{\mathrm{opt}} = v_z, \tag{8}$$

where GHA is Greenwich sidereal time. v_y has the same sign as $\sin(\lambda_{\mathrm{opt}} + \mathrm{GHA})$. The latitude, λ_{opt}, is measured positively east of Greenwich.

To calculate atmospheric refraction, R, we use at sea level the formula of Sæmundsson (**3**):

$$R = 1{\cdot}02 \cot\left(h + \frac{10{\cdot}3}{h + 5{\cdot}11}\right), \tag{9}$$

where h is the object's true altitude above the horizontal in degrees, and the result R is in minutes of arc. At other heights, tables from The Air Almanac (**4**) can be consulted.

The dip in the horizon is given by $D = -0'{\cdot}97\sqrt{h}$, where h is the observer's height above sea level in feet. For the lower limb of the Sun to be on the observer's horizon, its zenithal distance will be

$$z_{\odot} = 90° - \theta_{\odot} - D + R_{\odot} + \pi_{\odot}, \tag{10}$$

where $\theta_{\odot} = 16'$ is taken for the solar angular semidiameter. The refraction, $R_{\odot}$, is that calculated for an object at true zenithal distance $z_{\odot} + \theta_{\odot}$. This gives the required zenithal distance as $z_{\odot} = 90' \ 19'$, $91° \ 37'$, $92° \ 11'$ and $93° \ 58'$ at a height of 0, 5000, 10000 and 40000 ft respectively. The Moon's altitude above the visible horizon can then be obtained from

$$\bar{h}_{\mathrm{m}} = \sin^{-1}(\mathbf{r}_0 \cdot \mathbf{r}_{\mathrm{m}}) - D + R_{\mathrm{m}} - \pi_{\mathrm{m}}, \tag{11}$$

where π_{m} is the Moon's horizontal parallax, and the refraction, R_{m}, is evaluated for an object at a true altitude of $\sin^{-1}(\mathbf{r}_0 \cdot \mathbf{r}_{\mathrm{m}}) - \pi_{\mathrm{m}}$. The result will vary slightly from eclipse to eclipse, depending on the geocentric distances of the Sun and Moon and hence the angle subtended by the Earth's shadow at the distance of the Moon.

In these calculations, because of the vagaries of atmospheric refraction at low altitudes, high accuracy is not appropriate. We therefore do not apply a correction for the figure of the Earth, and list the results only to an accuracy of about 1′.

The Appendix table lists the universal time, UT, and Greenwich sidereal time, GHA, at the four contacts for a total eclipse and two for a partial eclipse. The assumed value of $\Delta T = TD - UT$, the difference between dynamical time and universal time, is listed for each eclipse. The actual value of ΔT_{obs} can only be determined by observation closer to the time of the eclipse. The tabulated values of universal time must be corrected by adding an amount $\Delta T - \Delta T_{\mathrm{obs}}$ to obtain the actual value for UT. The optimum longitude, $\lambda_{\rm opt}$, will move westwards by an amount 0·004178 $(\Delta T - \Delta T_{\rm obs})$ in units of degrees, with ΔT expressed in seconds. Also given are right ascension and declination of the Sun, $\alpha_\odot$, $\delta_\odot$, and of the Moon, $\alpha_{\rm m}$, $\delta_{\rm m}$. The optimum longitude, $\lambda_{\rm opt}$, optimum latitude $\phi_{\rm opt}$ and height, $\bar{h}_{\rm m}$, of the Moon above the visible horizon are given for observers at 0, 5000, 10000 and 40000 ft. At the listed optimum locations, the lower limb of the Sun will be observed on the horizon and the Moon is at its maximum possible altitude. The results were obtained using the method described above. Contact times were taken from reference (1) and the positions of the Sun and Moon were calculated using C language libraries written by J.Sax based on the methods described in reference (5).

By moving in a direction away from the Sun, the view of the twilight wedge and the Moon in shadow will be improved, as both will rise further above the horizon.

At first contact, the optimum location lies at low latitudes near the Earth's sunset terminator. As the eclipse progresses, it follows the terminator to high latitudes crossing the polar region and then moving from high to low latitudes down the sunrise terminator.

3 THE MOON'S ALTITUDE AT OTHER LATITUDES

In order to observe both the Sun and the Moon during a lunar eclipse, it is important to choose a location that maximizes the altitude of the Moon above the observer's horizon at critical times. The altitude of the Moon, for a fixed altitude of the Sun, varies only slowly as the observer moves away from the optimal latitude calculated above. In this section it is shown how to calculate the altitude of the Moon at any latitude once the zenithal distance of the Sun has been specified.

Let ϕ be the observer's latitude, and, as before, $z_\odot$ be the required zenithal distance of the Sun. The observer's longitude, λ, can then be obtained from

$$\cos H_\odot = \frac{\cos z_\odot - \sin\phi \sin\delta_\odot}{\cos\phi\cos\delta_\odot}, \qquad (12)$$

in which $H_\odot = \lambda + \mathrm{GHA} - \alpha_\odot$ is the hour angle of the Sun at the required location. The true altitude of the Moon above the horizontal is then obtained from the relation

$$\sin h_{\rm m} = \sin\phi\sin\delta_{\rm m} + \cos\phi\cos\delta_{\rm m}\cos H_{\rm m}, \qquad (13)$$

where $H_{\rm m} = \lambda + \mathrm{GHA} - \alpha_{\rm m}$ is the hour angle of the Moon.

The true altitude must be corrected for the dip of the horizon, refraction and parallax in order to obtain the height $\bar{h}_{\rm m}$ of the Moon above the observer's visible horizon as in equation (11):

$$\bar{h}_{\rm m} = h_{\rm m} + R_{\rm m} - D - \pi_{\rm m}, \qquad (14)$$

with the refraction $R_{\rm m}$ being evaluated for an object at true altitude $h_{\rm m}$ above the horizontal.

The altitude changes only slowly with latitude, so the exact choice of latitude for the location where observations are to be made is not critical. The choice of longitude, however, is of key importance. Locations at higher latitudes are to be favoured slightly because of the fact that the altitudes of the Sun and the Moon change more slowly with time here than in tropical regions.

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(5) Meeus, J., 1991. *Astronomical Algorithms*. Willmann-Bell, Richmond.

APPENDIX TABLE

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10000 ft) λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10000 ft) ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10000 ft) $\bar{h}_m$(40000 ft)
4 April, 1996			$\Delta T = 61{\cdot}9$ s		
$-1^h39^m{\cdot}2$	$0^h53^m{\cdot}2$	$12^h49^m{\cdot}3$	−63° 53′	+2° 29′	+0° 45′
$11^h11^m{\cdot}9$	+5° 42′	−5° 39′	−62° 34′	+2° 21′	+3° 02′
			−62° 00′	+2° 17′	+4° 00′
			−60° 14′	+2° 06′	+7° 15′
$-0^h33^m{\cdot}5$	$0^h53^m{\cdot}3$	$12^h51^m{\cdot}6$	−82° 11′	−16° 01′	+0° 18′
$12^h17^m{\cdot}8$	+5° 43′	−5° 50′	−80° 50′	−16° 09′	+2° 33′
			−80° 14′	−16° 12′	+3° 31′
			−78° 23′	−16° 21′	+6° 44′
$0^h53^m{\cdot}1$	$0^h53^m{\cdot}6$	$12^h54^m{\cdot}7$	+83° 53′	−49° 58′	+0° 18′
$13^h44^m{\cdot}6$	+5° 44′	−6° 04′	+81° 51′	−50° 08′	+2° 33′
			+80° 58′	−50° 12′	+3° 31′
			+78° 11′	−50° 22′	+6° 44′
$1^h58^m{\cdot}8$	$0^h53^m{\cdot}7$	$12^h57^m{\cdot}0$	+64° 14′	−31° 28′	+0° 45′
$14^h50^m{\cdot}5$	+5° 45′	−6° 15′	+62° 42′	−31° 36′	+3° 02′
			+62° 03′	−31° 40′	+4° 00′
			+59° 57′	−31° 49′	+7° 15′
27 September, 1996			$\Delta T = 62{\cdot}2$ s		
$1^h12^m{\cdot}2$	$12^h15^m{\cdot}5$	$0^h11^m{\cdot}4$	−110° 03′	+1° 50′	+0° 46′
$1^h37^m{\cdot}7$	−1° 40′	+1° 42′	−108° 44′	+1° 52′	+3° 03′
			−108° 10′	+1° 53′	+4° 01′
			−106° 23′	+1° 56′	+7° 16′
$2^h19^m{\cdot}2$	$12^h15^m{\cdot}6$	$0^h14^m{\cdot}0$	−127° 37′	+28° 09′	+0° 18′
$2^h44^m{\cdot}9$	−1° 42′	+1° 55′	−126° 08′	+28° 11′	+2° 32′
			−125° 29′	+28° 12′	+3° 31′
			−123° 28′	+28° 12′	+6° 44′
$3^h29^m{\cdot}4$	$12^h15^m{\cdot}8$	$0^h16^m{\cdot}6$	+38° 12′	+63° 44′	+0° 18′
$3^h55^m{\cdot}3$	−1° 43′	+2° 08′	+35° 13′	+63° 47′	+2° 32′
			+33° 56′	+63° 47′	+3° 31′
			+29° 54′	+63° 43′	+6° 44′
$4^h36^m{\cdot}4$	$12^h16^m{\cdot}0$	$0^h19^m{\cdot}2$	+19° 35′	+37° 19′	+0° 45′
$5^h02^m{\cdot}4$	−1° 44′	+2° 21′	+17° 56′	+37° 21′	+3° 03′
			+17° 13′	+37° 21′	+4° 01′
			+14° 58′	+37° 21′	+7° 16′

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10000 ft) λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10000 ft) ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10000 ft) $\bar{h}_m$(40000 ft)
24 March, 1997		$\Delta T = 62{\cdot}6$ s			
$4^h39^m{\cdot}4$	$0^h12^m{\cdot}9$	$12^h10^m{\cdot}4$	−130° 49′	+47° 08′	+0° 44′
$15^h05^m{\cdot}0$	+1° 24′	−0° 44′	−128° 53′	+47° 03′	+3° 01′
			−128° 03′	+47° 01′	+4° 00′
			−125° 27′	+46° 51′	+7° 51′
$6^h21^m{\cdot}4$	$0^h13^m{\cdot}4$	$12^h17^m{\cdot}0$	−4° 22′	+11° 51′	+0° 44′
$18^h29^m{\cdot}5$	+1° 27′	−1° 16′	−5° 43′	+11° 49′	+3° 01′
			−6° 18′	+11° 48′	+4° 00′
			−8° 07′	+11° 44′	+7° 15′
16 September, 1997		$\Delta T = 63{\cdot}0$ s			
$17^h07^m{\cdot}9$	$11^h37^m{\cdot}5$	$23^h34^m{\cdot}2$	+10° 07′	−39° 02′	+0° 46′
$16^h51^m{\cdot}7$	+2° 26′	−3° 06′	+11° 48′	−39° 05′	+3° 03′
			+12° 32′	−39° 06′	+4° 02′
			+14° 50′	−39° 08′	+7° 17′
$18^h15^m{\cdot}4$	$11^h37^m{\cdot}6$	$23^h36^m{\cdot}9$	−10° 31′	−68° 32′	+0° 17′
$17^h59^m{\cdot}4$	+2° 25′	−2° 53′	−6° 55′	−68° 37′	+2° 32′
			−5° 22′	−68° 39′	+3° 30′
			−0° 29′	−68° 36′	+6° 43′
$19^h17^m{\cdot}8$	$11^h37^m{\cdot}8$	$23^h39^m{\cdot}4$	+160° 28′	−33° 41′	+0° 17′
$19^h01^m{\cdot}9$	+2° 24′	−2° 41′	+158° 53′	−33° 45′	+2° 32′
			+158° 12′	−33° 46′	+3° 30′
			+156° 04′	−33° 47′	+6° 43′
$20^h25^m{\cdot}3$	$11^h38^m{\cdot}0$	$23^h42^m{\cdot}2$	+142° 12′	−3° 49′	+0° 46′
$20^h09^m{\cdot}6$	+2° 23′	−2° 27′	+140° 53′	−3° 52′	+3° 03′
			+140° 19′	−3° 54′	+4° 02′
			+138° 32′	−3° 58′	+7° 17′
28 July, 1999		$\Delta T = 64{\cdot}4$ s			
$11^h33^m{\cdot}7$	$8^h29^m{\cdot}1$	$20^h26^m{\cdot}2$	+133° 30′	+40° 11′	+0° 45′
$6^h45^m{\cdot}7$	+19° 02′	−18° 24′	+135° 02′	+39° 36′	+3° 02′
			+135° 42′	+39° 21′	+4° 00′
			+137° 43′	+38° 31′	+7° 15′
$12^h45^m{\cdot}4$	$8^h29^m{\cdot}5$	$20^h31^m{\cdot}4$	−129° 25′	+54° 39′	+0° 45′
$9^h09^m{\cdot}4$	+19° 01′	−18° 12′	−131° 15′	+53° 53′	+3° 02′
			−132° 01′	+53° 33′	+4° 00′
			−134° 22′	+52° 28′	+7° 15′
21 January, 2000		$\Delta T = 64{\cdot}8$ s			
$3^h01^m{\cdot}3$	$20^h10^m{\cdot}2$	$8^h05^m{\cdot}9$	−128° 48′	−9° 21′	+0° 46′
$11^h01^m{\cdot}6$	−20° 04′	+19° 53′	−127° 33′	−8° 53′	+3° 03′
			−127° 01′	−8° 41′	+4° 01′
			−125° 20′	−8° 03′	+7° 16′
$4^h04^m{\cdot}5$	$20^h10^m{\cdot}4$	$8^h08^m{\cdot}7$	−136° 09′	−29° 19′	+0° 17′
$12^h05^m{\cdot}0$	−20° 04′	+19° 49′	−134° 47′	−28° 47′	+2° 32′
			−134° 11′	−28° 33′	+3° 30′
			−132° 21′	−27° 49′	+6° 43′

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_{\odot}$ $\delta_{\odot}$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10 000 ft) λ_{opt}(40 000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10 000 ft) ϕ_{opt}(40 000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10 000 ft) $\bar{h}_m$(40 000 ft)
$5^h22^m{\cdot}5$	$20^h10^m{\cdot}7$	$8^h12^m{\cdot}1$	−7° 11′	−41° 34′	+0° 17′
$13^h23^m{\cdot}2$	−20° 03′	+19° 42′	−8° 44′	−40° 57′	+2° 32′
			−9° 23′	−40° 40′	+3° 30′
			−11° 25′	−39° 47′	+6° 43′
$6^h25^m{\cdot}7$	$20^h10^m{\cdot}8$	$8^h14^m{\cdot}9$	−12° 26′	−21° 55′	+0° 46′
$14^h26^m{\cdot}5$	−20° 02′	+19° 37′	−13° 45′	−21° 26′	+3° 03′
			−14° 19′	−21° 13′	+4° 01′
			−16° 05′	−20° 31′	+7° 16′
16 July, 2000		$\Delta T = 65{\cdot}2$ s			
$11^h57^m{\cdot}0$	$7^h44^m{\cdot}6$	$19^h40^m{\cdot}7$	+91° 36′	−2° 31′	+0° 44′
$7^h36^m{\cdot}6$	+21° 16′	−21° 18′	+92° 50′	−3° 00′	+3° 01′
			+93° 22′	−3° 12′	+4° 00′
			+95° 02′	−3° 51′	+7° 15′
$13^h01^m{\cdot}8$	$7^h44^m{\cdot}8$	$19^h43^m{\cdot}0$	+76° 10′	−0° 35′	+0° 19′
$8^h41^m{\cdot}6$	+21° 15′	−21° 16′	+77° 23′	−1° 03′	+2° 34′
			+77° 55′	−1° 16′	+3° 32′
			+79° 35′	−1° 54′	+6° 45′
$14^h49^m{\cdot}2$	$7^h45^m{\cdot}1$	$19^h46^m{\cdot}8$	−134° 03′	+7° 33′	+0° 19′
$10^h29^m{\cdot}3$	+21° 15′	−21° 11′	−135° 17′	+7° 04′	+2° 34′
			−135° 49′	+6° 52′	+3° 32′
			−137° 29′	+6° 12′	+6° 45′
$15^h54^m{\cdot}0$	$7^h45^m{\cdot}2$	$19^h49^m{\cdot}1$	−149° 29′	+5° 37′	+0° 44′
$11^h34^m{\cdot}2$	+21° 14′	−21° 08′	−150° 43′	+5° 08′	+3° 01′
			−151° 15′	+4° 55′	+4° 00′
			−152° 55′	+4° 16′	+7° 15′
9 January, 2001		$\Delta T = 65{\cdot}6$ s			
$18^h41^m{\cdot}9$	$19^h24^m{\cdot}8$	$7^h20^m{\cdot}6$	−17° 46′	+22° 09′	+0° 46′
$2^h00^m{\cdot}5$	−22° 01′	+22° 26′	−16° 28′	+22° 40′	+3° 03′
			−15° 54′	+22° 54′	+4° 01′
			−14° 06′	+23° 35′	+7° 16′
$19^h49^m{\cdot}6$	$19^h25^m{\cdot}0$	$7^h23^m{\cdot}7$	−52° 09′	+48° 26′	+0° 17′
$3^h08^m{\cdot}3$	−22° 00′	+22° 24′	−50° 28′	+49° 10′	+2° 31′
			−49° 44′	+49° 28′	+3° 30′
			−47° 22′	+50° 24′	+6° 43′
$20^h51^m{\cdot}6$	$19^h25^m{\cdot}2$	$7^h26^m{\cdot}5$	+161° 37′	+44° 15′	+0° 17′
$4^h10^m{\cdot}5$	−22° 00′	+22° 22′	+160° 02′	+44° 55′	+2° 31′
			+159° 20′	+45° 12′	+3° 30′
			+157° 06′	+46° 04′	+6° 43′
$21^h59^m{\cdot}3$	$19^h25^m{\cdot}4$	$7^h29^m{\cdot}6$	+128° 56′	+17° 22′	+0° 46′
$5^h18^m{\cdot}4$	−21° 59′	+22° 19′	+127° 40′	+17° 53′	+3° 03′
			+127° 07′	+18° 06′	+4° 01′
			+125° 22′	+18° 46′	+7° 16′

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10000 ft) λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10000 ft) ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10000 ft) $\bar{h}_m$(40000 ft)
5 July, 2001		$\Delta T = 66{\cdot}0$ s			
$14^h55^m{\cdot}3$	$6^h59^m{\cdot}0$	$18^h56^m{\cdot}3$	+45° 15′	−42° 28′	+0° 44′
$8^h30^m{\cdot}8$	+22° 45′	−23° 25′	+46° 48′	−43° 09′	+3° 01′
			+47° 28′	−43° 26′	+4° 00′
			+49° 38′	−44° 18′	+7° 15′
$16^h15^m{\cdot}4$	$6^h59^m{\cdot}5$	$19^h02^m{\cdot}2$	−130° 54′	−42° 08′	+0° 44′
$11^h11^m{\cdot}4$	+22° 44′	−23° 24′	−132° 26′	−42° 48′	+3° 02′
			−133° 06′	−43° 05′	+4° 00′
			−135° 16′	−43° 56′	+7° 15′
16 May, 2003		$\Delta T = 67{\cdot}4$ s			
$2^h02^m{\cdot}7$	$3^h29^m{\cdot}9$	$15^h26^m{\cdot}6$	−104° 15′	+40° 14′	+0° 46′
$17^h37^m{\cdot}3$	+18° 58′	−18° 15′	−102° 42′	+39° 40′	+3° 03′
			−102° 03′	+39° 24′	+4° 02′
			−100° 01′	+38° 35′	+7° 17′
$3^h13^m{\cdot}8$	$3^h30^m{\cdot}0$	$15^h29^m{\cdot}6$	−82° 27′	+67° 20′	+0° 17′
$18^h48^m{\cdot}6$	+18° 59′	−18° 30′	−80° 46′	+66° 12′	+2° 32′
			−80° 05′	+65° 42′	+3° 30′
			−78° 06′	+64° 07′	+6° 43′
$4^h06^m{\cdot}4$	$3^h30^m{\cdot}2$	$15^h31^m{\cdot}8$	+12° 33′	+36° 06′	+0° 17′
$19^h41^m{\cdot}4$	+19° 00′	−18° 41′	+11° 04′	+35° 33′	+2° 32′
			+10° 26′	+35° 19′	+3° 30′
			+8° 29′	+34° 32′	+6° 43′
$5^h17^m{\cdot}5$	$3^h30^m{\cdot}4$	$15^h34^m{\cdot}8$	+8° 08′	+3° 40′	+0° 46′
$20^h52^m{\cdot}7$	+19° 00′	−18° 56′	+6° 53′	+3° 14′	+3° 03′
			+6° 21′	+3° 03′	+4° 02′
			+4° 40′	+2° 28′	+7° 17′
9 November, 2003		$\Delta T = 67{\cdot}8$ s			
$-0^h27^m{\cdot}6$	$14^h54^m{\cdot}7$	$2^h52^m{\cdot}2$	−68° 53′	−45° 37′	+0° 44′
$2^h44^m{\cdot}5$	−16° 40′	+16° 00′	−67° 11′	−45° 04′	+3° 01′
			−66° 28′	−44° 49′	+3° 59′
			−64° 14′	−44° 00′	+7° 14′
$1^h06^m{\cdot}7$	$14^h55^m{\cdot}0$	$2^h55^m{\cdot}2$	+9° 35′	−70° 31′	+0° 19′
$4^h19^m{\cdot}0$	−16° 41′	+16° 18′	+7° 47′	−69° 21′	+2° 33′
			+7° 04′	−68° 51′	+3° 32′
			+5° 00′	−67° 14′	+6° 45′
$1^h30^m{\cdot}3$	$14^h55^m{\cdot}0$	$2^h56^m{\cdot}0$	+41° 01′	−51° 06′	+0° 19′
$4^h42^m{\cdot}7$	−16° 42′	+16° 22′	+39° 11′	−50° 28′	+2° 33′
			+38° 25′	−50° 11′	+3° 32′
			+36° 02′	−49° 17′	+6° 45′
$3^h04^m{\cdot}6$	$14^h55^m{\cdot}3$	$2^h59^m{\cdot}0$	+38° 32′	−3° 11′	+0° 44′
$6^h17^m{\cdot}3$	−16° 43′	+16° 39′	+37° 16′	−2° 48′	+3° 01′
			+36° 43′	−2° 38′	+3° 59′
			+35° 01′	−2° 07′	+7° 14′

APPENDIX TABLE CONTINUED

UT / GHA	$\alpha_\odot$ / $\delta_\odot$	α_m / δ_m	λ_{opt}(0 ft) / λ_{opt}(5000 ft) / λ_{opt}(10000 ft) / λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) / ϕ_{opt}(5000 ft) / ϕ_{opt}(10000 ft) / ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) / $\bar{h}_m$(5000 ft) / $\bar{h}_m$(10000 ft) / $\bar{h}_m$(40000 ft)
4 May, 2004		$\Delta T = 68{\cdot}2$ s			
$18^{h}48^{m}{\cdot}1$	$2^{h}48^{m}{\cdot}7$	$14^{h}44^{m}{\cdot}3$	−11° 08′	+4° 47′	+0° 46′
$9^{h}41^{m}{\cdot}2$	+16° 14′	−16° 08′	−9° 52′	+4° 25′	+3° 03′
			−9° 20′	+4° 16′	+4° 02′
			−7° 37′	+3° 45′	+7° 17′
$19^{h}52^{m}{\cdot}0$	$2^{h}48^{m}{\cdot}8$	$14^{h}46^{m}{\cdot}9$	−33° 37′	−17° 00′	+0° 18′
$10^{h}45^{m}{\cdot}3$	+16° 14′	−16° 23′	−32° 17′	−17° 23′	+2° 32′
			−31° 43′	−17° 32′	+3° 30′
			−29° 55′	−18° 02′	+6° 43′
$21^{h}08^{m}{\cdot}4$	$2^{h}49^{m}{\cdot}0$	$14^{h}49^{m}{\cdot}9$	+160° 47′	−59° 18′	+0° 17′
$12^{h}01^{m}{\cdot}9$	+16° 15′	−16° 41′	+158° 34′	−59° 59′	+2° 32′
			+157° 35′	−60° 16′	+3° 30′
			+154° 23′	−61° 07′	+6° 43′
$22^{h}12^{m}{\cdot}3$	$2^{h}49^{m}{\cdot}2$	$14^{h}52^{m}{\cdot}5$	+129° 12′	−38° 41′	+0° 46′
$13^{h}06^{m}{\cdot}0$	+16° 16′	−16° 56′	+127° 37′	−39° 08′	+3° 03′
			+126° 55′	−39° 19′	+4° 01′
			+124° 44′	−39° 54′	+7° 16′
28 October, 2004		$\Delta T = 68{\cdot}6$ s			
$1^{h}14^{m}{\cdot}2$	$14^{h}10^{m}{\cdot}7$	$2^{h}06^{m}{\cdot}9$	−110° 18′	−8° 28′	+0° 44′
$3^{h}42^{m}{\cdot}3$	−13° 11′	+13° 02′	−109° 00′	−8° 10′	+3° 01′
			−108° 26′	−8° 02′	+4° 00′
			−106° 42′	−7° 36′	+7° 15′
$2^{h}23^{m}{\cdot}3$	$14^{h}10^{m}{\cdot}9$	$2^{h}09^{m}{\cdot}2$	−132° 42′	+13° 10′	+0° 18′
$4^{h}51^{m}{\cdot}5$	−13° 12′	+13° 17′	−131° 23′	+13° 28′	+2° 33′
			−130° 49′	+13° 36′	+3° 31′
			−129° 02′	+13° 59′	+6° 44′
$3^{h}44^{m}{\cdot}7$	$14^{h}11^{m}{\cdot}1$	$2^{h}11^{m}{\cdot}9$	+54° 11′	+61° 03′	+0° 18′
$6^{h}13^{m}{\cdot}2$	−13° 13′	+13° 36′	+51° 44′	+61° 38′	+2° 33′
			+50° 39′	+61° 52′	+3° 31′
			+47° 07′	+62° 34′	+6° 44′
$4^{h}53^{m}{\cdot}8$	$14^{h}11^{m}{\cdot}3$	$2^{h}14^{m}{\cdot}2$	+23° 40′	+40° 30′	+0° 44′
$7^{h}22^{m}{\cdot}5$	−13° 14′	+13° 51′	+22° 00′	+40° 53′	+3° 02′
			+21° 17′	+41° 02′	+4° 00′
			+19° 00′	+41° 30′	+7° 15′
17 October, 2005		$\Delta T = 69{\cdot}4$ s			
$12^{h}03^{m}{\cdot}2$	$13^{h}29^{m}{\cdot}6$	$1^{h}26^{m}{\cdot}9$	+83° 04′	+46° 45′	+0° 45′
$13^{h}19^{m}{\cdot}8$	−9° 23′	+10° 07′	+84° 56′	+47° 02′	+3° 02′
			+85° 45′	+47° 09′	+4° 01′
			+88° 21′	+47° 29′	+7° 16′
$12^{h}32^{m}{\cdot}0$	$13^{h}29^{m}{\cdot}8$	$1^{h}28^{m}{\cdot}9$	+41° 23′	+75° 05′	+0° 45′
$14^{h}17^{m}{\cdot}6$	−9° 24′	+10° 23′	+45° 38′	+75° 52′	+3° 02′
			+47° 37′	+76° 10′	+4° 01′
			+54° 22′	+77° 01′	+7° 16′

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10000 ft) λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10000 ft) ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10000 ft) $\bar{h}_m$(40000 ft)
7 September, 2006		$\Delta T = 70{\cdot}1$ s			
$18^h 51^m{\cdot}2$ $17^h 12^m{\cdot}9$	$11^h 04^m{\cdot}7$ $+5° 55'$	$23^h 04^m{\cdot}8$ $-6° 58'$	$-114° 52'$ $-120° 52'$ $-124° 25'$ $-142° 31'$	$-83° 54'$ $-85° 05'$ $-85° 34'$ $-86° 55'$	$+0° 46'$ $+3° 03'$ $+4° 02'$ $+7° 17'$
$19^h 37^m{\cdot}4$ $18^h 45^m{\cdot}5$	$11^h 04^m{\cdot}9$ $+5° 54'$	$23^h 08^m{\cdot}3$ $-6° 31'$	$+159° 02'$ $+157° 25'$ $+156° 43'$ $+154° 31'$	$-35° 46'$ $-35° 55'$ $-35° 58'$ $-36° 08'$	$+0° 46'$ $+3° 03'$ $+4° 02'$ $+7° 17'$
3 March, 2007		$\Delta T = 70{\cdot}5$ s			
$21^h 29^m{\cdot}9$ $8^h 16^m{\cdot}2$	$22^h 57^m{\cdot}0$ $-6° 43'$	$10^h 54^m{\cdot}6$ $+7° 22'$	$-56° 12'$ $-54° 18'$ $-53° 29'$ $-50° 53'$	$+46° 35'$ $+46° 47'$ $+46° 52'$ $+47° 04'$	$+0° 44'$ $+3° 01'$ $+3° 59'$ $+7° 14'$
$22^h 43^m{\cdot}7$ $9^h 30^m{\cdot}2$	$22^h 57^m{\cdot}2$ $-6° 41'$	$10^h 56^m{\cdot}8$ $+7° 05'$	$-88° 41'$ $-84° 31'$ $-82° 40'$ $-76° 37'$	$+72° 29'$ $+72° 56'$ $+73° 06'$ $+73° 30'$	$+0° 19'$ $+2° 33'$ $+3° 32'$ $+6° 45'$
$23^h 57^m{\cdot}9$ $10^h 44^m{\cdot}6$	$22^h 57^m{\cdot}4$ $-6° 40'$	$10^h 59^m{\cdot}0$ $+6° 47'$	$+95° 13'$ $+93° 51'$ $+93° 16'$ $+91° 24'$	$+16° 51'$ $+17° 00'$ $+17° 04'$ $+17° 16'$	$+0° 19'$ $+2° 33'$ $+3° 32'$ $+6° 45'$
$25^h 11^m{\cdot}7$ $11^h 58^m{\cdot}6$	$22^h 57^m{\cdot}6$ $-6° 39'$	$11^h 01^m{\cdot}2$ $+6° 30'$	$+73° 37'$ $+72° 18'$ $+71° 44'$ $+69° 56'$	$-9° 31'$ $-9° 22'$ $-9° 18'$ $-9° 04'$	$+0° 44'$ $+3° 01'$ $+3° 59'$ $+7° 14'$
28 August, 2007		$\Delta T = 70{\cdot}9$ s			
$8^h 50^m{\cdot}7$ $7^h 16^m{\cdot}7$	$10^h 26^m{\cdot}2$ $+9° 48'$	$22^h 23^m{\cdot}0$ $-10° 26'$	$+130° 09'$ $+131° 48'$ $+132° 31'$ $+134° 46'$	$-38° 34'$ $-38° 50'$ $-38° 57'$ $-39° 16'$	$+0° 46'$ $+3° 03'$ $+4° 01'$ $+7° 16'$
$9^h 51^m{\cdot}8$ $8^h 18^m{\cdot}0$	$10^h 26^m{\cdot}3$ $+9° 47'$	$22^h 25^m{\cdot}2$ $-10° 10'$	$+109° 48'$ $+111° 55'$ $+112° 50'$ $+115° 45'$	$-52° 45'$ $-53° 06'$ $-53° 14'$ $-53° 36'$	$+0° 18'$ $+2° 32'$ $+3° 31'$ $+6° 44'$
$11^h 22^m{\cdot}6$ $9^h 49^m{\cdot}0$	$10^h 26^m{\cdot}6$ $+9° 45'$	$22^h 28^m{\cdot}5$ $-9° 45'$	$-80° 40'$ $-81° 58'$ $-82° 32'$ $-84° 17'$	$+0° 18'$ $+0° 04'$ $-0° 01'$ $-0° 20'$	$+0° 18'$ $+2° 32'$ $+3° 31'$ $+6° 44'$
$12^h 23^m{\cdot}7$ $10^h 50^m{\cdot}3$	$10^h 26^m{\cdot}7$ $+9° 44'$	$22^h 30^m{\cdot}7$ $-9° 29'$	$-98° 29'$ $-99° 50'$ $-100° 24'$ $-102° 13'$	$+14° 42'$ $+14° 28'$ $+14° 22'$ $+14° 02'$	$+0° 46'$ $+3° 03'$ $+4° 01'$ $+7° 16'$

Appendix Table continued

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10 000 ft) λ_{opt}(40 000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10 000 ft) ϕ_{opt}(40 000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10 000 ft) $\bar{h}_m$(40 000 ft)
21 February, 2008		$\Delta T = 71{\cdot}3$ s			
$1^h42^m{\cdot}8$	$22^h15^m{\cdot}2$	$10^h11^m{\cdot}3$	−112° 35′	+3° 14′	+0° 45′
$11^h45^m{\cdot}5$	−10° 50′	+10° 53′	−111° 17′	+3° 29′	+3° 02′
			−110° 44′	+3° 35′	+4° 00′
			−108° 58′	+3° 55′	+7° 15′
$3^h00^m{\cdot}5$	$22^h15^m{\cdot}4$	$10^h14^m{\cdot}0$	−124° 13′	−32° 57′	+0° 18′
$13^h03^m{\cdot}4$	−10° 49′	+10° 34′	−122° 42′	−32° 38′	+2° 33′
			−122° 02′	−32° 30′	+3° 31′
			−120° 00′	−32° 03′	+6° 44′
$3^h51^m{\cdot}3$	$22^h15^m{\cdot}6$	$10^h15^m{\cdot}7$	−39° 14′	−78° 31′	+0° 18′
$13^h54^m{\cdot}3$	−10° 48′	+10° 22′	−40° 46′	−77° 14′	+2° 33′
			−41° 20′	−76° 41′	+3° 31′
			−42° 51′	−74° 56′	+6° 44′
$5^h09^m{\cdot}0$	$22^h15^m{\cdot}8$	$10^h18^m{\cdot}3$	+3° 09′	−48° 47′	+0° 45′
$15^h12^m{\cdot}2$	−10° 47′	+10° 03′	+1° 15′	−48° 23′	+3° 02′
			+0° 27′	−48° 12′	+4° 00′
			−2° 03′	−47° 36′	+7° 15′
16 August, 2008		$\Delta T = 71{\cdot}8$ s			
$21^h10^m{\cdot}0$	$9^h46^m{\cdot}4$	$21^h42^m{\cdot}5$	−20° 27′	+8° 41′	+0° 45′
$17^h19^m{\cdot}0$	+13° 26′	−13° 17′	−19° 09′	+8° 22′	+3° 02′
			−18° 36′	+8° 14′	+4° 00′
			−16° 51′	+7° 48′	+7° 15′
$22^h44^m{\cdot}5$	$9^h46^m{\cdot}9$	$21^h48^m{\cdot}9$	+88° 12′	+56° 33′	+0° 45′
$20^h28^m{\cdot}5$	+13° 23′	−12° 34′	+86° 04′	+55° 58′	+3° 02′
			+85° 10′	+55° 42′	+4° 00′
			+82° 26′	+54° 50′	+7° 15′
31 December, 2009		$\Delta T = 72{\cdot}9$ s			
$19^h22^m{\cdot}5$	$18^h44^m{\cdot}5$	$6^h44^m{\cdot}0$	−84° 37′	+66° 16′	+0° 46′
$1^h34^m{\cdot}2$	−23° 03′	+24° 04′	−83° 39′	+67° 32′	+3° 03′
			−83° 13′	+68° 04′	+4° 01′
			−81° 41′	+69° 46′	+7° 16′
$19^h53^m{\cdot}3$	$18^h44^m{\cdot}7$	$6^h46^m{\cdot}8$	−170° 05′	+55° 27′	+0° 45′
$2^h36^m{\cdot}0$	−23° 02′	+23° 58′	−171° 50′	+56° 20′	+3° 03′
			−172° 36′	+56° 43′	+4° 01′
			−175° 08′	+57° 51′	+7° 16′
26 June, 2010		$\Delta T = 73{\cdot}3$ s			
$11^h38^m{\cdot}3$	$6^h20^m{\cdot}6$	$18^h18^m{\cdot}1$	+89° 32′	−47° 01′	+0° 45′
$4^h35^m{\cdot}4$	+23° 21′	−24° 05′	+91° 08′	−47° 46′	+3° 02′
			+91° 50′	−48° 05′	+4° 00′
			+94° 07′	−49° 03′	+7° 15′
$13^h00^m{\cdot}2$	$6^h21^m{\cdot}0$	$18^h24^m{\cdot}3$	−87° 57′	−33° 48′	+0° 45′
$7^h19^m{\cdot}6$	+23° 21′	−23° 55′	−89° 21′	−34° 25′	+3° 02′
			−89° 58′	−34° 40′	+4° 00′
			−91° 55′	−35° 28′	+7° 15′

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10000 ft) λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10000 ft) ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10000 ft) $\bar{h}_m$(40000 ft)
21 December, 2010		$\Delta T = 73{\cdot}7$ s			
$6^h32^m{\cdot}0$ $12^h32^m{\cdot}1$	$17^h56^m{\cdot}8$ $-23°\ 26'$	$5^h52^m{\cdot}9$ $+23°\ 50'$	$+161°\ 44'$ $+163°\ 02'$ $+163°\ 35'$ $+165°\ 21'$	$+22°\ 01'$ $+22°\ 35'$ $+22°\ 49'$ $+23°\ 33'$	$+0°\ 45'$ $+3°\ 02'$ $+4°\ 00'$ $+7°\ 15'$
$7^h40^m{\cdot}1$ $13^h40^m{\cdot}4$	$17^h57^m{\cdot}0$ $-23°\ 26'$	$5^h55^m{\cdot}8$ $+23°\ 47'$	$+130°\ 00'$ $+131°\ 34'$ $+132°\ 14'$ $+134°\ 26'$	$+44°\ 13'$ $+44°\ 56'$ $+45°\ 14'$ $+46°\ 09'$	$+0°\ 18'$ $+2°\ 32'$ $+3°\ 31'$ $+6°\ 44'$
$8^h53^m{\cdot}5$ $14^h54^m{\cdot}0$	$17^h57^m{\cdot}3$ $-23°\ 26'$	$5^h58^m{\cdot}8$ $+23°\ 43'$	$-26°\ 44'$ $-28°\ 09'$ $-28°\ 46'$ $-30°\ 44'$	$+34°\ 50'$ $+35°\ 28'$ $+35°\ 44'$ $+36°\ 32'$	$+0°\ 18'$ $+2°\ 32'$ $+3°\ 31'$ $+6°\ 44'$
$10^h01^m{\cdot}6$ $16^h02^m{\cdot}3$	$17^h57^m{\cdot}5$ $-23°\ 26'$	$6^h01^m{\cdot}7$ $+23°\ 39'$	$-55°\ 53'$ $-57°\ 07'$ $-57°\ 39'$ $-59°\ 20'$	$+12°\ 08'$ $+12°\ 40'$ $+12°\ 53'$ $+13°\ 36'$	$+0°\ 45'$ $+3°\ 02'$ $+4°\ 00'$ $+7°\ 15'$
15 June, 2011		$\Delta T = 74{\cdot}1$ s			
$18^h22^m{\cdot}3$ $11^h58^m{\cdot}3$	$5^h35^m{\cdot}2$ $+23°\ 19'$	$17^h30^m{\cdot}9$ $-23°\ 17'$	$-4°\ 27'$ $-3°\ 15'$ $-2°\ 43'$ $-1°\ 05'$	$+1°\ 34'$ $+1°\ 03'$ $+0°\ 49'$ $+0°\ 07'$	$+0°\ 45'$ $+3°\ 03'$ $+4°\ 01'$ $+7°\ 16'$
$19^h21^m{\cdot}9$ $12^h58^m{\cdot}1$	$5^h35^m{\cdot}4$ $+23°\ 19'$	$17^h33^m{\cdot}4$ $-23°\ 15'$	$-17°\ 01'$ $-15°\ 49'$ $-15°\ 17'$ $-13°\ 39'$	$+6°\ 56'$ $+6°\ 24'$ $+6°\ 10'$ $+5°\ 27'$	$+0°\ 18'$ $+2°\ 33'$ $+3°\ 31'$ $+6°\ 44'$
$21^h03^m{\cdot}1$ $14^h39^m{\cdot}5$	$5^h35^m{\cdot}7$ $+23°\ 19'$	$17^h37^m{\cdot}7$ $-23°\ 12'$	$+128°\ 23'$ $+127°\ 09'$ $+126°\ 37'$ $+124°\ 58'$	$+12°\ 50'$ $+12°\ 18'$ $+12°\ 04'$ $+11°\ 19'$	$+0°\ 18'$ $+2°\ 33'$ $+3°\ 31'$ $+6°\ 44'$
$22^h02^m{\cdot}7$ $15^h39^m{\cdot}3$	$5^h35^m{\cdot}9$ $+23°\ 19'$	$17^h40^m{\cdot}2$ $-23°\ 10'$	$+115°\ 52'$ $+114°\ 39'$ $+114°\ 08'$ $+112°\ 29'$	$+7°\ 31'$ $+6°\ 59'$ $+6°\ 46'$ $+6°\ 02'$	$+0°\ 45'$ $+3°\ 03'$ $+4°\ 01'$ $+7°\ 16'$
10 December, 2011		$\Delta T = 74{\cdot}6$ s			
$12^h45^m{\cdot}0$ $18^h01^m{\cdot}9$	$17^h08^m{\cdot}3$ $-22°\ 54'$	$5^h04^m{\cdot}6$ $+22°\ 33'$	$+86°\ 17'$ $+87°\ 33'$ $+88°\ 06'$ $+89°\ 48'$	$-20°\ 21'$ $-19°\ 48'$ $-19°\ 34'$ $-18°\ 47'$	$+0°\ 44'$ $+3°\ 01'$ $+4°\ 00'$ $+7°\ 15'$
$14^h05^m{\cdot}6$ $19^h22^m{\cdot}7$	$17^h08^m{\cdot}5$ $-22°\ 55'$	$5^h07^m{\cdot}6$ $+22°\ 33'$	$+90°\ 22'$ $+91°\ 59'$ $+92°\ 39'$ $+94°\ 43'$	$-52°\ 10'$ $-51°\ 19'$ $-50°\ 56'$ $-49°\ 44'$	$+0°\ 18'$ $+2°\ 33'$ $+3°\ 31'$ $+6°\ 44'$

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10000 ft) λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10000 ft) ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10000 ft) $\bar{h}_m$(40000 ft)
$14^{h}57^{m}{\cdot}6$	$17^{h}08^{m}{\cdot}7$	$5^{h}09^{m}{\cdot}5$	−171° 37′	−53° 26′	+0° 18′
$20^{h}14^{m}{\cdot}8$	−22° 55′	+22° 33′	−173° 15′	−52° 33′	+2° 33′
			−173° 56′	−52° 10′	+3° 31′
			−175° 59′	−50° 55′	+6° 44′
$16^{h}18^{m}{\cdot}2$	$17^{h}08^{m}{\cdot}9$	$5^{h}12^{m}{\cdot}5$	−166° 22′	−21° 37′	+0° 44′
$21^{h}35^{m}{\cdot}6$	−22° 55′	+22° 33′	−167° 39′	−21° 03′	+3° 01′
			−168° 12′	−20° 48′	+3° 59′
			−169° 54′	−20° 02′	+7° 14′
4 June, 2012		$\Delta T = 75{\cdot}0$ s			
$11^{h}03^{m}{\cdot}1$	$4^{h}51^{m}{\cdot}4$	$16^{h}48^{m}{\cdot}7$	+148° 16′	+48° 32′	+0° 46′
$2^{h}53^{m}{\cdot}6$	+22° 30′	−21° 39′	+149° 51′	+47° 45′	+3° 03′
			+150° 32′	+47° 24′	+4° 02′
			+152° 35′	+46° 18′	+7° 17′
$12^{h}06^{m}{\cdot}9$	$4^{h}51^{m}{\cdot}7$	$16^{h}54^{m}{\cdot}5$	−118° 41′	+46° 38′	+0° 46′
$5^{h}01^{m}{\cdot}5$	+22° 31′	−21° 41′	−120° 14′	+45° 53′	+3° 03′
			−120° 54′	+45° 33′	+4° 02′
			−122° 56′	+44° 29′	+7° 17′
25 April, 2013		$\Delta T = 75{\cdot}8$ s			
$20^{h}07^{m}{\cdot}4$	$2^{h}13^{m}{\cdot}8$	$14^{h}12^{m}{\cdot}2$	−58° 02′	−64° 40′	+0° 46′
$10^{h}09^{m}{\cdot}7$	+13° 26′	−14° 23′	−55° 29′	−65° 21′	+3° 03′
			−54° 17′	−65° 37′	+4° 01′
			−50° 22′	−66° 26′	+7° 16′
$20^{h}22^{m}{\cdot}3$	$2^{h}13^{m}{\cdot}9$	$14^{h}13^{m}{\cdot}5$	−101° 24′	−75° 35′	+0° 46′
$10^{h}39^{m}{\cdot}6$	+13° 27′	−14° 28′	−99° 03′	−76° 46′	+3° 03′
			−97° 55′	−77° 17′	+4° 01′
			−93° 40′	−78° 50′	+7° 16′
15 April, 2014		$\Delta T = 76{\cdot}6$ s			
$5^{h}57^{m}{\cdot}7$	$1^{h}33^{m}{\cdot}4$	$13^{h}29^{m}{\cdot}5$	−179° 23′	−1° 42′	+0° 45′
$19^{h}32^{m}{\cdot}3$	+9° 45′	−9° 46′	−178° 06′	−1° 55′	+3° 02′
			−177° 32′	−2° 01′	+4° 00′
			−175° 46′	−2° 19′	+7° 15′
$7^{h}06^{m}{\cdot}1$	$1^{h}33^{m}{\cdot}6$	$13^{h}31^{m}{\cdot}9$	+159° 20′	−24° 29′	+0° 18′
$20^{h}40^{m}{\cdot}9$	+9° 46′	−9° 57′	+160° 46′	−24° 43′	+2° 33′
			+161° 23′	−24° 49′	+3° 31′
			+163° 19′	−25° 06′	+6° 44′
$8^{h}24^{m}{\cdot}9$	$1^{h}33^{m}{\cdot}8$	$13^{h}34^{m}{\cdot}8$	−22° 21′	−55° 17′	+0° 18′
$21^{h}59^{m}{\cdot}9$	+9° 47′	−10° 09′	−24° 35′	−55° 39′	+2° 33′
			−25° 33′	−55° 47′	+3° 31′
			−28° 39′	−56° 11′	+6° 44′
$9^{h}33^{m}{\cdot}3$	$1^{h}33^{m}{\cdot}9$	$13^{h}37^{m}{\cdot}2$	−47° 19′	−32° 38′	+0° 45′
$23^{h}08^{m}{\cdot}5$	+9° 48′	−10° 19′	−48° 51′	−32° 53′	+3° 02′
			−49° 31′	−32° 59′	+4° 00′
			−51° 37′	−33° 17′	+7° 15′

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10000 ft) λ_{opt}(40000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10000 ft) ϕ_{opt}(40000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10000 ft) $\bar{h}_m$(40000 ft)
8 October, 2014		$\Delta T = 77{\cdot}0$ s			
$9^{h}14^{m}{\cdot}2$	$12^{h}55^{m}{\cdot}3$	$0^{h}51^{m}{\cdot}2$	+128° 08′	+4° 55′	+0° 46′
$10^{h}23^{m}{\cdot}2$	−5° 55′	+6° 00′	+129° 27′	+5° 03′	+3° 03′
			+130° 01′	+5° 07′	+4° 01′
			+131° 48′	+5° 17′	+7° 16′
$10^{h}24^{m}{\cdot}5$	$12^{h}55^{m}{\cdot}5$	$0^{h}54^{m}{\cdot}0$	+106° 46′	+36° 18′	+0° 17′
$11^{h}33^{m}{\cdot}7$	−5° 56′	+6° 13′	+108° 23′	+36° 27′	+2° 32′
			+109° 05′	+36° 30′	+3° 30′
			111° 18′	+36° 40′	+6° 43′
$11^{h}24^{m}{\cdot}3$	$12^{h}55^{m}{\cdot}6$	$0^{h}56^{m}{\cdot}3$	−68° 37′	+69° 49′	+0° 17′
$12^{h}33^{m}{\cdot}7$	−5° 57′	+6° 24′	−72° 20′	+70° 09′	+2° 32′
			−73° 58′	+70° 16′	+3° 30′
			−79° 14′	+70° 33′	+6° 43′
$12^{h}34^{m}{\cdot}6$	$12^{h}55^{m}{\cdot}8$	$0^{h}59^{m}{\cdot}0$	−97° 19′	+38° 50′	+0° 46′
$13^{h}44^{m}{\cdot}2$	−5° 58′	+6° 37′	−99° 00′	+38° 59′	+3° 03′
			−99° 43′	+39° 03′	+4° 01′
			−102° 01′	+39° 13′	+7° 16′
4 April, 2015		$\Delta T = 77{\cdot}5$ s			
$10^{h}15^{m}{\cdot}2$	$0^{h}52^{m}{\cdot}8$	$12^{h}50^{m}{\cdot}1$	+122° 45′	+43° 22′	+0° 44′
$23^{h}06^{m}{\cdot}2$	+5° 39′	−5° 01′	+124° 32′	+43° 10′	+3° 01′
			+125° 18′	+43° 04′	+4° 00′
			+127° 41′	+42° 45′	+7° 15′
$11^{h}55^{m}{\cdot}8$	$0^{h}53^{m}{\cdot}0$	$12^{h}53^{m}{\cdot}4$	−113° 47′	+76° 23′	+0° 19′
$0^{h}47^{m}{\cdot}0$	+5° 40′	−5° 17′	−118° 36′	+75° 45′	+2° 33′
			−120° 32′	+75° 27′	+3° 32′
			−126° 07′	+74° 25′	+6° 45′
$12^{h}04^{m}{\cdot}4$	$0^{h}53^{m}{\cdot}0$	$12^{h}53^{m}{\cdot}6$	−105° 07′	+67° 37′	+0° 19′
$0^{h}55^{m}{\cdot}7$	+5° 41′	−5° 18′	−108° 23′	+67° 14′	+2° 33′
			−109° 46′	+67° 02′	+3° 32′
			−113° 57′	+66° 22′	+6° 45′
$13^{h}45^{m}{\cdot}0$	$0^{h}53^{m}{\cdot}3$	$12^{h}56^{m}{\cdot}9$	−116° 45′	+9° 34′	+0° 44′
$2^{h}36^{m}{\cdot}5$	+5° 42′	−5° 33′	−118° 05′	+9° 26′	+3° 01′
			−118° 39′	+9° 22′	+4° 00′
			−120° 27′	+9° 10′	+7° 15′
28 September, 2015		$\Delta T = 77{\cdot}9$ s			
$1^{h}06^{m}{\cdot}6$	$12^{h}16^{m}{\cdot}9$	$0^{h}13^{m}{\cdot}5$	−107° 13′	−36° 19′	+0° 46′
$1^{h}33^{m}{\cdot}9$	−1° 50′	+1° 12′	−105° 35′	−36° 15′	+3° 03′
			−104° 53′	−36° 13′	+4° 02′
			−102° 41′	−36° 04′	+7° 17′
$2^{h}10^{m}{\cdot}6$	$12^{h}17^{m}{\cdot}1$	$0^{h}16^{m}{\cdot}1$	−121° 03′	−60° 31′	+0° 17′
$2^{h}38^{m}{\cdot}1$	−1° 51′	+1° 25′	−118° 24′	−60° 24′	+2° 32′
			117° 16′	−60° 19′	+3° 30′
			−113° 43′	−60° 02′	+6° 43′

APPENDIX TABLE CONTINUED

UT GHA	$\alpha_\odot$ $\delta_\odot$	α_m δ_m	λ_{opt}(0 ft) λ_{opt}(5000 ft) λ_{opt}(10 000 ft) λ_{opt}(40 000 ft)	ϕ_{opt}(0 ft) ϕ_{opt}(5000 ft) ϕ_{opt}(10 000 ft) ϕ_{opt}(40 000 ft)	$\bar{h}_m$(0 ft) $\bar{h}_m$(5000 ft) $\bar{h}_m$(10 000 ft) $\bar{h}_m$(40 000 ft)
$3^h 23^m \cdot 4$	$12^h 17^m \cdot 2$	$0^h 19^m \cdot 0$	$+35° 39'$	$-25° 17'$	$+0° 17'$
$3^h 51^m \cdot 1$	$-1° 52'$	$+1° 39'$	$+34° 12'$	$-25° 13'$	$+2° 32'$
			$+33° 35'$	$-25° 12'$	$+3° 30'$
			$+31° 37'$	$-25° 05'$	$+6° 43'$
$4^h 27^m \cdot 4$	$12^h 17^m \cdot 4$	$0^h 21^m \cdot 6$	$+20° 32'$	$-0° 56'$	$+0° 46'$
$4^h 55^m \cdot 3$	$-1° 53'$	$+1° 52'$	$+19° 13'$	$-0° 54'$	$+3° 03'$
			$+18° 39'$	$-0° 53'$	$+4° 02'$
			$+16° 52'$	$-0° 49'$	$+7° 17'$