

USNO/AA Technical Note 2016-04

Further Analysis of the Mount Wilson Sunset Observations

James L. Hilton

November 17, 2016

Abstract

The calculated time of sunset in Hilton (2014a) to analyze the sunset times observed by Rarogiewicz (1994) were computed using an early version of SLAC 2.0. A second analysis is made here using a significantly improved refraction algorithm. The change in the calculated times of sunset do not change significantly from those of the preliminary analysis.

Rarogiewicz (1994) also contains previously un-analyzed observations of the time of contact of the lower limb and the center of the Sun with the horizon. These lower limb and center contact observations are found to agree generally with the refraction at large zenith distances calculated using the modified standard atmosphere model rather than the observed times of sunset. The difference may be explained by the combination of: a thin (few hundred meter thick) atmospheric boundary layer, irradiation¹, and the rapid change in illumination that occurs at sunset.

A more detailed analysis of the profile of the Channel Islands shows, conclusively, that they cannot have any affect on the observations.

1. Introduction

Hilton (2014a) made four suggestions for additional analysis of the sunset observations contained in Rarogiewicz (1994). The first two recommendations are:

1. The analysis should be repeated using the updated version of the refraction functions found in the final version SLAC 2.0.
2. The Rarogiewicz (1994) observations also include 109 observations of contact of the solar lower limb (LL) and 217 observations of contact of the solar center with the horizon. These data should be analyzed as well.

Does the final SLAC 2.0 refraction model modify the initial conclusions? What additional information can be derived from the observations of LL and center contact with horizon? This technical

¹A physiological effects encountered in observing an object significantly brighter than its surroundings.

note addresses these two questions. Section 2 describes the differences between the preliminary and final SLAC 2.0 refraction procedures and how those change the calculated time of sunset. Section 3 reevaluates the observations and discusses the possible effects of observations with remarks and light wavelength on the analysis. Section 4 describes the analysis of the LL and center contact data.

Hilton (2014a) also points out that the mountains of the Channel Islands are high enough that they could affect the observed time of sunset if an observed sunset occurs in the azimuth range of these islands. Hilton concluded that this phenomenon was not likely, but only rough estimates of the azimuth range of the islands and sunsets were used. The possibility of an overlap of ranges was likely enough that a more accurate estimate of the possibility of the islands interfering with sunset observations is made in § 5.

The analysis of the Mount Wilson observations in this technical note demonstrates that much more can be done to provided accurate predictions of refraction at large zenith distances and related phenomena. Section 6 discusses additional activities to improve such predictions.

2. Differences Between the Initial and Updated Refraction Procedures

The calculated times of sunset in Hilton (2014a) were determined using an early version of the refraction functions written for SLAC 2.0. These functions use the algorithm described in Hohenkerk & Sinclair (1985). The final version of SLAC 2.0 includes several improvements detailed in Hohenkerk & Sinclair (2008) and Hilton (2014b). The differences between the initial and final versions are:

- improved algorithms for the saturation pressure of water vapor, and the gravitational acceleration with latitude and height,
- adjustment for the change in distance from the geocenter to the ellipsoid with latitude, and
- improved values for the Earth's equatorial radius, the gas constant, and the molecular

Table 1: The statistical properties of the ($O - C$)s of sunset times for the Mount Wilson sunset observations.

Group	No.	Mean (s)	Median (s)	σ (s)	Skew
θ	178	41	35	58	0.032
P	55	114	101	77	0.283
N	17	204	190	77	0.845
All	250	68	53	80	0.738

masses of dry air and water.

The model atmosphere still consists of:

- A troposphere extending from the ellipsoid to 11 km. The temperature with height is the recorded temperature at the observer with an assumed lapse rate of 6.5 K km^{-1} . The partial pressure of water vapor with height is the relative humidity at the observer and Eq. 38 of Hilton (2014b).
- A dry, isothermal stratosphere extending from 11 to 80 km above the ellipsoid. The stratosphere temperature is assumed to be the same as the troposphere temperature at the tropopause².

3. The Observations

Rarogiewicz (1994) made a total of 250 observations of the sunset time and local atmospheric conditions at Mount Wilson. The circumstances of these observations are described in Hilton (2014a). Rarogiewicz also observed the times of contact with the horizon of the solar LL on 109 occasions and the solar center on 217 occasions along with the sunset times.

Rarogiewicz classified the observations in two ways: First, he gave a judgement of the “quality” of the observation into the categories of: A – Best, B – Good, C – Fair, Q – Questionable, and U – Unknown. Second he judged whether or not the observation included the *Novaya Zemlya* effect into categories of: 0 – None, P – Partial, N – *Novaya Zemlya* effect. Hilton (2014a) showed that the quality categories had no significant effect on the observed sunset times, but the *Novaya Zemlya* effect categories were a significant indicator of difference in the mean sunset time ($O - C$). Table 1, from Hilton (2014a), summarizes the effect of the *Novaya Zemlya* effect label had on the time of sunset.

3.1. Observations with Remarks

A number of observations have remarks made by the observer. These remarks such as, “Sun may

²The interface between the troposphere and the stratosphere.

Table 2: Distribution of observations with remarks.

Group	Number of Observations		
	Sunset	Center	Lower Limb
0	12	11	0
P	2	2	0
N	1	1	1
All	15	14	1

have set into distant smog layer,” suggest that the observing conditions on that day may have had an affect on observing the horizon. The number of these observations is small, and their distribution with observation type is in Table 2. The observations were analyzed in three groups: observations without remarks, observations with remarks, and all observations. The results for all three groups did not differ significantly.

The most frequent comment was that the Sun appeared to set into a distant “smog layer”. One explanation for this comment is: The observer is noticing a large increase in the opacity of the atmosphere arising from the long distance the photons travel through the relatively dense lower atmosphere (see for example Zinkova, 2015a). The increase in opacity can be quite sudden in the case of the *Novaya Zemlya* effect (see for example Zinkova, 2015b)³. The Sun may also appear to set a distance above the horizon. This phenomenon is caused by the location of the light duct, not smog.

Two other remarks are, “Little flickering ‘speckles’ (??) of light seen at horizon sunset azimuth point (moving slowly N-wards) continued for minutes after actual sunset,” and “Sun appeared to set into line parallel to and just above true horizon.” The first observation is marked as being a *Novaya Zemlya* observation, and the second is marked as a partial-*Novaya Zemlya* observation. Both of these behaviors can be attributed to the light duct which forms on these occasions. Zinkova (2015b) shows both behaviors.

The observations with remarks do not appear to be problematic. The number of observations with remarks is small fraction of the total, so removing them does not significantly affect the results. The results reported here consist of the subset of observations *without* remarks.

3.2. The Effect of Wavelength

The refraction of light is a function of its wavelength. The SLAC refraction function determines the refraction at a single wavelength. In the initial analysis, wavelength used to calculated the time

³In this example the light duct is noticeable appearing as a slightly darker band where the “square” image of the Sun is visible.

Table 3: Difference in calculated Mount Wilson sunset observations.

Wavelength (nm)	Difference		
	Mean (s)	Max. (s)	Min (s)
501.7	0.46±0.07	0.65	0.27
600	-1.02±0.10	-0.77	-1.31
700	-1.92±0.17	-1.57	-2.39

of sunset was 501.7 nm. This wavelength is in the green portion of the visible spectrum near the peak of solar radiation. Near sunset, however, the Sun can appear to be orange (~590–620 nm) and even red (~620–750 nm). Preferential scattering of shorter wavelength radiation by the Earth’s atmosphere causes the apparent color change. The time of sunset was calculated at 600 and 700 nm as well as 501.7 nm to determine if the difference in refraction with wavelength was a significant factor.

The difference between the time of sunset using initial and final versions of the SLAC 2.0 refraction procedures is summarized in Table 3. The differences are given in terms of original minus new value. So, a negative value represents a *later* calculated time of sunset. At 501.7 nm the changes to the algorithm decreases the mean time of sunset by an insignificant 0.5 s. At 700 nm the mean time of sunset increases of 1.9 s. This difference is equivalent to a upward displacement in the apparent limb of the Sun of $29 \pm 3''$ compared to its position at 501.7 nm. The increase in sunset time arising from using a more appropriate wavelength is only 3.5% of the mean (O – C) difference for all the observed sunsets and 5.9% of the (O – C) difference for those sunsets identified as having no *Novaya Zemlya* effect. Thus, changing the wavelength to one more representative of the predominant wavelength observed at sunset does decrease the mean absolute value of the (O – C)s, but the change is too small to account for the observed sunset times.

4. Analysis of LL and Center Contact Data

The ephemeris functions in SLAC return the positions of the center and upper limb of an extended body. To get the altitude of the upper limb an offset is applied to the unrefracted altitude of the center. The time of rise and set is then the time at which the refracted position of the upper limb matches that of the apparent⁴ horizon. Applying the same offset for the position of the upper limb with the opposite sign gives the altitude of the LL, assuming the body is spherical. This change was

⁴Including dip.

Table 4: The mean (O – C) of different phenomena.

Group	LL (s)	Center (s)	Sunset (s)
0	4.1±45.9	-4.1±31.2	41.9±59.1
P	-0.4±47.0	-0.6±45.3	115.9±77.1
N	1.7±26.3	-12.7±30.2	202.7±79.8
All	3.1±44.9	-4.1±34.9	69.5±80.3

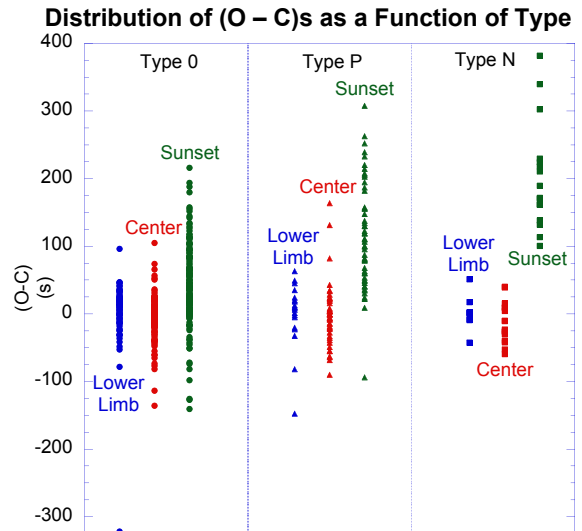


Figure 1: The distributions of the (O – C)s of LL and center contact and sunset by sunset type.

made to the SLAC code along with modification to the SLAC rise-set-transit functions to find the time of LL and center contact with the apparent horizon.

The observed times of LL and center contact are summarized in Table 4 and Fig. 1. The observed mean times of LL and center contact are in better agreement with their calculated times than are the times of sunset, and the standard deviations for LL and center contact are smaller than for the time of sunset. The mean differences are stable for all groups of LL and center contact observations although there is a large change in the mean (O – C) values for sunset between the groups. The smaller standard deviation for observations of the center contact is particularly surprising since determination of the position of the Sun’s center is more difficult than it is to determine the position of its limb.

Three hypotheses, decoherence, irradiation, and apparent depth of the surface layer (SL) are examined as possible explanations for the difference in the (O – C)s of LL and center contact compared to those of sunset. The apparent depth of the SL appears to be the most likely of these three hypotheses.

4.1. Decoherence

The first hypothesis for lack of a correlation is: short term variations in the atmosphere cause some decoherence in the refraction angle at the horizon between the times of LL contact, center contact, and sunset. Hohenkerk & Sinclair (2008) estimate the change in the refraction angle from changes in air pressure and temperature are $+2''.3 \text{ mb}^{-1}$ and $-13''.6 \text{ K}^{-1}$, respectively. To achieve the mean difference observed between the time of LL contact and sunset the atmospheric pressure would need to increase at a rate of 230 mb min^{-1} or the temperature would need to decrease at a rate of 39 K min^{-1} . Neither rates of change are likely. Nor is a large enough combined change in pressure and temperature likely. Thus, decoherence is not a likely source for the lack of correlation between sunset, LL contact and center contact.

4.2. Irradiation

These observations were all made using the human eye as the detector; usually with the aid of binoculars. So the observed time of the phenomena are subject to physiological as well as physical effects. Do physiological effects result in a different timing for sunset than the two other phenomena?

Irradiation (Minnaert, 1974, pg. 127) is the physiological effect that makes a bright object such as the Sun or bright limb of the Moon appear larger than the dimmer background surrounding it. Westheimer (2007) demonstrates that irradiation is a function of the contrast in brilliancy between the object and its background, and the maximum increase in the apparent size of the of an object by about $3'$ for the greatest contrast. The apparent increase in size leads to a difference in the times of LL and center contact of about 12 s. The change is in the correct direction, but is too small to account for the observed difference. Nor can irradiation account for the observation that the RMS for the LL and center contact (O - C)s are approximately one-half those for the sunset time observations.

4.3. Apparent Depth of the Surface Layer (SL)

The greatest contributor to the refraction of an astronomical object observed at zenith distances $\sim 90^\circ$ is the SL *near the horizon*, the point where the photon path is tangent to the Earth's surface. The SL is defined (Stull, 1988, pg. 10) as the bottom 10% of the atmospheric boundary layer⁵. The depths and temperature profiles of the atmospheric

⁵The atmospheric boundary layer is defined as: That part of the troposphere directly influenced by the presence of the Earth's surface, and responding to surface forcings on a timescale of about an hour (Stull, 1988, pg. 2).

boundary layer and SL are functions of the local geography, meteorology, and solar irradiation⁶. The SL temperature profile is strongly affected by the temperature and thermal inertia of the Earth's surface. A useful approximation for the depth of the SL is $\sim 200 \text{ m}$.

For most observers the distance to the apparent horizon is a few kilometers, and both the observer and the horizon are situated in the same local volume of the SL. For an observer on Mount Wilson, the distance to the horizon is $\sim 150 \text{ km}$, and the apparent angular height of the SL is $\sim 5'$.

The sunset time is when the apparent upper limb Sun disappears below the apparent horizon, which is marked change in contrast. The times of LL and center contact *are* determined by observing when that portion of the apparent Sun comes in contact with the apparent horizon, but there is no marked change. The effect of the apparent depth of the SL results in a difference in how these phenomena were observed.

The observed times of LL and center contact are primarily function of the atmosphere above the SL, possibly modified by irradiation. Above the SL, the adopted model atmospheric temperature and humidity profiles are a good approximation of the model atmosphere both at the observer and at the horizon. This assumption is consistent with the principle that the atmosphere becomes more uniform with height (e.g. Stull, 2006).

The combined mean (O - C) of LL and center contact is $-1.6 \pm 38.6 \text{ s}$. This agreement suggests that the theory of refraction is accurate to approximately $-6''.4$ at a geometric zenith distance of about $91^\circ 5$. Excellent agreement considering the large uncertainties in the atmospheric model and the large distance between the observer and the horizon.

The observed sunset time, however, is primarily a function of refraction of the light passing through the SL. Within the SL temperature and humidity profiles are not well modeled, but are significantly modified by the presence and temperature of the sea surface.

- The atmosphere for that part of the atmospheric boundary layer above the SL is well represented by the model atmosphere. The standard deviations of the differences between the observed and calculated times of LL and center contact are more than a factor of two smaller than those for sunset. This observation is consistent with the principle that the atmosphere becomes more uniform with height (e.g. Stull, 2006).

⁶Irradiation is used here in its physical sense of being exposed to radiation rather than its physiological sense used in § 4.2.

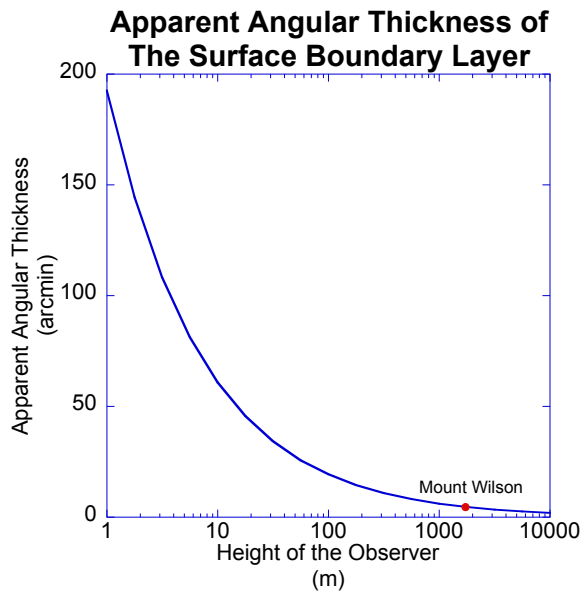


Figure 2: The apparent depth of the SL as a function of the observer’s height above the surrounding terrain.

4.3.1. Mount Wilson

This explanation for the differences between the (O – C)s of the times of sunset and those of LL and center contact applies specifically to the Mount Wilson observations. The high altitude of the observer above the sea horizon results in a small apparent angular height to the SL for this case. The apparent angular height of the SL is greater, and the observed times of LL and center contact likely have greater correlation with the observed rather than the calculated time of sunset for more usual circumstances. The estimated apparent angular depth of the SL is shown in Fig. 2. The value at Mount Wilson is designated by the red point. The apparent angular depth will be greater than the apparent diameters of the Sun and Moon, about 30’ for observers less than 40 m above the surrounding terrain.

The temperature profile within the local, Mount Wilson, SL likely had little effect on the observations for several reasons:

- The SL at Mount Wilson was probably thin because it is elevated well above its local surroundings.
- The observations were made late in the day. This is the time period during which the atmospheric boundary layer is most likely to be homogenous because:
 - daytime convection of the atmosphere tends to homogenize the atmosphere,
 - there is little heating of the surface from solar irradiation, and
 - the thermal inertia of the surface is relatively small.

- By definition, the primary source of the departure of the atmospheric boundary layer and SL from the free atmosphere is the effect of the Earth’s surface. So, the SL tends to follow the contours of the land. At Mount Wilson these contours slope down to the west causing the SL boundary to tilt towards the west reducing the refraction angle in that direction.

5. The Azimuth of Sunset

One possible problem with observing the sunset from Mount Wilson is the Channel Islands⁷. The islands of Santa Cruz and Anacapa are visible along the western horizon from Mount Wilson. Figure 3 shows the rough outlines of these two islands derived from topographic maps (USGS, 1982, 1984). The vertical distances are exaggerated by a factor of 8.325 over the horizontal distances.

The shorelines of these islands should be visible although they are below the geometric horizon. Young (2004) and Sweer (1938) estimate that for an observer at the height of Mount Wilson, the refraction from the observer to the point where the light ray grazes the ellipsoid is approximately 44% of the astronomical refraction. This refraction angle varies from about 8’5 at the shoreline to about 7’3 at the highest point. Thus, the shorelines are visible and the apparent height is compressed about 10% compared to their geometric height.

Anacapa Island subtends the horizon from an azimuth of approximately 257° to 258°, and Santa Cruz Island subtends the horizon from an azimuth of approximately 258° to 263.°5. None of the observed sunsets or other phenomena occurred at an azimuth between 255° and 264°. Thus, these islands were not a factor in any of the observations.

6. Discussion

The 250 sunset observation includes 15 observations with remarks. These remarks indicate that there may have been problems with observing the times of sunset. The data were examined with and without these remarkable observations. These observations were also analyzed alone. The results arising from the remarkable observations were not found to differ significantly from those of the rest. Examination of other observations of sunsets such as Zinkova (2015a,b) indicate that the remarks may have been observations of atmospheric phenomena associated with the refraction and not obscurations such as distant smog or clouds. These observations were *not* included in the final analysis to remove

⁷It is also possible that there may be foreground objects that interrupt the horizon. Available data do not indicate the existence of any such foreground objects.

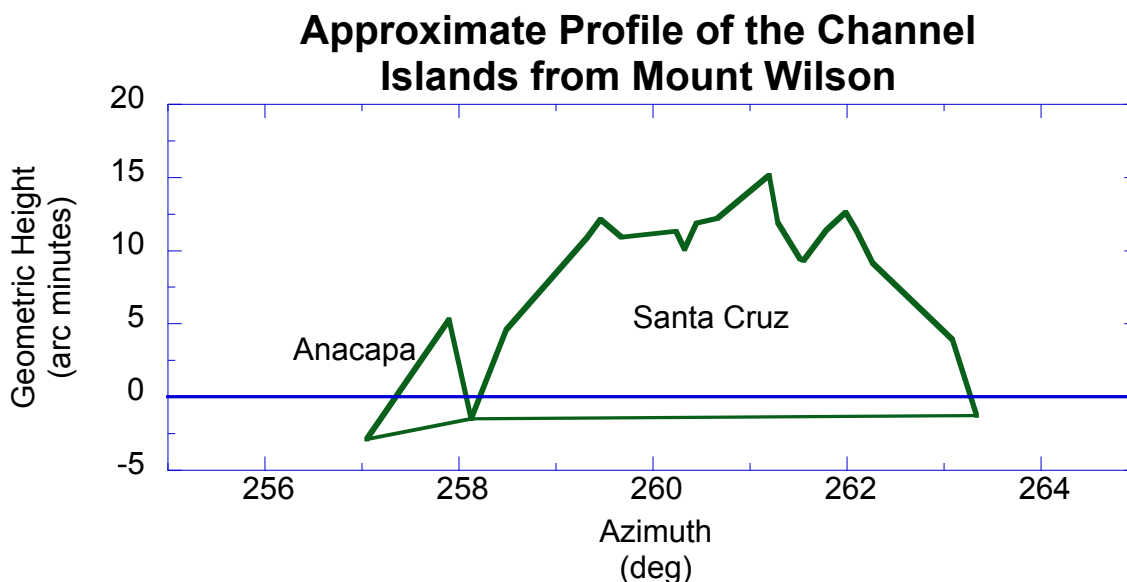


Figure 3: The rough apparent geometric outlines of Anacapa Island and Santa Cruz Island as viewed from Mount Wilson. The vertical distance is exaggerated by a factor of 8.325 compared to the horizontal distance.

any possibility of biasing the results.

The observations of sunsets from Mount Wilson were initially reduced using an early version of the algorithm used for SLAC 2.0 at a wavelength of 501.7 nm, approximately at the peak of the solar emissions as a function of wavelength. Several improvements were made to the algorithm since that time. Also, at sunset most of the bluer wavelengths of the Sun's light is scattered by the Earth's atmosphere making the Sun appear red. Re-reduction of the observations using the updated algorithm finds a mean decrease of approximately 0.5 s in the calculated time of sunset using the revised at the original wavelength. Increasing the wavelength to 700 nm, the approximate red extreme of the visible spectrum, increased the mean calculated time of sunset by 1.9 s compared to the the original value. These differences are insignificant compared to the mean values of the (O - C)s.

The mean difference between the observed and calculated times of sunset is a factor of 36 greater than the change arising from the revised algorithm and using a more appropriate wavelength to calculate the time of sunset. The revised model does *not* include a SL temperature profile that varies from the U.S. 1976 Standard Atmosphere. A better temperature profile for the SL is the change most likely to reduce the (O - C)s.

In addition to the 250 sunset observations the observer made 109 observations of the contact of the solar LL with the horizon and 217 observations of the contact of the solar center with the horizon. These data have only a small correlation between the time of the contact of the solar center with the horizon and the time of sunset and *no* correlation between the time of the contact of the solar LL

with the horizon and the time of sunset. There is a stronger correlation between the observed and calculated times of these phenomena. The working explanation is:

- The difference between the calculated and observed times of these phenomena arises primarily because of the SL temperature profile *at the horizon*.
- From Mount Wilson the SL appears to be $\sim 5'$ thick at the distant horizon.
- Irradiation, in the physiological sense, makes a bright object appear $\sim 3'$ larger against a dark background.
- For the cases of LL and center contact: The combination of irradiation and the apparent thinness of the SL combine to make the apparent time of contact independent of the light contribution passing through the SL.
- For the sunset case: The timing of the phenomenon is determined by the sudden disappearance of the upper limb, which is viewed *through* the SL.

Furthermore, the smaller standard deviations of the (O - C)s for LL and center contact compared to the standard deviation of the (O - C)s for sunset qualitatively demonstrates that the adopted atmosphere model is more accurate where the perturbation by the Earth's surface become less significant with increasing height.

None of the observed phenomena took place within the span of azimuth in which the Channel Islands lie. So, they are not a factor in these observations.

6.1. The Temperature Profile of the Surface Layer

The greatest contributor to the refraction of an astronomical object observed at zenith distances $\sim 90^\circ$ is the SL *near the horizon*. The distance to the horizon for most observations of phenomena at large zenith distances is a few kilometers. Thus, the observer is located in the same local volume of the SL as the horizon, and the atmospheric conditions recorded at the observer should be indicative of those near the horizon.

For the Mount Wilson observations the observer is at a height of about 1770 m above the ellipsoid with clear view of a horizon approximately on the ellipsoid⁸. The distance to the horizon is ~ 150 km. The atmospheric conditions recorded at the observer are within the same mesoscale (Stull, 2006) weather system as the atmospheric conditions near the horizon⁹. The late afternoon, overland temperature at the observer is likely a good indication of the mixing layer¹⁰ at the observer’s height above the ellipsoid (Stull, 1988, Figure 1.12), which should be approximately the same over the extent of the weather system. The temperature profile of the SL over the ocean, however, is likely to include a strong inversion in the 10–20 m above the surface because of the large thermal inertia of the water. This hypothesized inversion layer is the source of the increased refraction responsible for the large positive differences in the observed (O – C)s.

The short apparent height of the SL is demonstrated by the better agreement in the (O – C)s of the times of LL and center contact compared with the time of sunset observed at Mount Wilson.

Further analysis of the Mount Wilson observations to determine the effect of a possible inversion layer requires two significant activities:

1. Acquire temperature records for locations closer to the horizon than the observer at Mount Wilson and
2. Modify the computer model to accommodate a troposphere temperature structure other than a constant lapse rate.

The *National Buoy Data Center* at NOAA provides historical records of sea water and air temperature for a number of locations of interest¹¹. Enough of these stations include data from the period of interest that a useful determination of the temper-

⁸There may be some local undulation of the geoid and the height of the waves on the ocean are not taken into account (Hilton, 2014a). Both of these are minor concerns.

⁹If the observer and the horizon are not within the same weather system, then adverse conditions, e.g. a frontal line, precluding the likelihood of observing the sunset is almost certain.

¹⁰The convective body of the atmospheric boundary layer, which extends from the SL to the capping inversion at the top of the atmospheric boundary layer.

¹¹http://www.ndbc.noaa.gov/maps/southwest_inset_hist.shtml. Retrieved March 21, 2016.

Table 5: The maximum uncertainty in the parameters required to determine the refraction angle with an accuracy of 0.1.

Parameter	Required Accuracy	Units
light wavelength	0.02	μm
atmospheric pressure	1.3	mbar
water vapor partial pressure	0.7*	mbar
temperature	0.2	K

*The equivalent accuracy in relative humidity is 60% at 10°C and 17% at 30°C.

ature profile near the horizon might be determined. The refraction model already accommodates a binary lapse rate model with different rates for the troposphere and stratosphere. Modification to accept a multi-lapse rate model could be instituted as an extension of this already existing binary model. Lehn & Morrish (1986) and Lehn & Friesen (1992) demonstrate that the model required to simulate observed effect of an inversion layer does not have to be complex.

6.2. Future Refraction Investigation

The greatest difficulty in determining the refraction at low altitudes is the temperature profile near the surface at the horizon. There are at least three methods to provide an improved profile:

Direct measurement: The SL is shallow enough that sensors attached to a small weather balloon or kite could be used to measure its profile. A full profile of the SL is not required to successfully model the refraction. Young (2004) and Lehn & Morrish (1986) demonstrate that the bottom five to ten meters of the SL is responsible for most of the non-standard refraction effect. This distance is small enough that it could be measured with a series of sensors attached to a mast.

A reasonable goal is to determine the refraction angle at a geometric zenith distance of 90° with an accuracy of 0.1. The sensors’ heights need to be determined with an accuracy of about 1 m, and Table 5 gives the accuracies of the atmospheric parameters required to achieve this goal. Except for the temperature, the accuracies of these parameters are quite modest.

Light, inexpensive sensors are generally available. A typical set of sensors is the SparkFun Weather Shield. It costs about \$40.00, and includes sensors for pressure, temperature, humidity, and light flux. The accuracy of its sensors are given in Table 6. The temperature sensor’s response time, 50 ms, is short compared to the rate of change of temperature and its long term drift is $0.04^\circ\text{C yr}^{-1}$. Performing an absolute calibration of the sensor

Table 6: Accuracy of the SparkFun Weather Shield sensors.

Parameter	Accuracy	Units
atmospheric pressure	0.5	mbar
water vapor partial pressure	0.06	mbar
temperature	0.3	K

and averaging three or four measurements should reduce the uncertainty in the temperature to reach the desired level of accuracy. The pressure sensor is accurate enough to determine the relative height with an accuracy of 0.3 m.

This method’s advantage is: It gives direct, real-time measurement of the temperature profile. Its disadvantages are it requires additional hardware and time to make the observations.

Infer the temperature profile from observation of refraction related phenomena: Observation of an extended source, such as the Sun, at a large zenith angle produces a distorted image. This image contains the data required to determine the SL temperature profile, which can be extracted from analysis of the image (Bruton, 1996). The object is not required to be an astronomical body. An object on or near the surface may be used if its undistorted shape is known and it is sufficiently near the horizon. It may also be possible to extract this data from timed observations of the zenith distance of a bright point source¹², such as a planet or first magnitude star.

This method’s advantage is: It requires no additional hardware. Its disadvantages are it requires an appropriate observable object and sophisticated analysis to extract the temperature profile from the data.

Establish a ‘dictionary’ of temperature profiles: The SL temperature profile is not arbitrary, but a function of a number of variables determined by the local climate factors (e.g. geography, season, weather, time of day, and sea surface temperature). So, making observations at of a number of local climate scenarios would produce a most likely temperature profile for a given set of circumstances. Application of this prior data would then reduce the uncertainty in the refraction angle at large zenith distances. It would also establish a better understanding of the uncertainties in the predicted values.

This method’s advantage is: It does not require large amounts of additional data at the time of observation. Thus, it may be the best for use in the field. It should result in a significant reduction in the uncertainty when refraction related phenomena

¹²Atmospheric absorption at large zenith distances can be large enough to cause significant extinction.

occur. Some of these phenomena, such as the *Novaya Zemlya* effect may delay the time of sunset by several minutes. The Mount Wilson data show that such phenomena are not uncommon even at mid-latitudes. Its disadvantage is it cannot guarantee an accurate estimate of the refraction angle. Instead, it would reduce the uncertainty in the angle. It is not clear by how much the uncertainty would be reduced since the literature does not appear to contain any analysis of the topic. A reasonable goal would be to reduce the mean (O – C) from a mean offset of 70 s with a standard deviation of 80 s to no offset and a standard deviation of 40 s. The equivalent uncertainty in the refraction angle at the horizon is 10’.

6.3. Data Sources

There are at least three possible sources for at least some of the data required to establish a ‘dictionary’ and more accurately define its limits.

1. Establish a program to take the required data. This program would require the establishment of a number of observatories to take the required data at enough locations over a long enough period of time to establish the most likely temperature profile given the observer’s place, time-of-day and general atmospheric conditions. The technology exists to construct inexpensive, autonomous platforms. Complete coverage would require observations from on the order of a hundred sites over a period of two or three years each.
2. Smiley (1950, 1951, 1952) summarizes the analysis of approximately 35,000 low altitude observations of the Sun made in the tropics, temperate zones, and polar regions. These observations may still be in existence in the Brown University archives. The index to Smiley’s papers indicate that there may be additional useful data, such as observations of the time of sunrise/set and twilight illumination made at the Ladd Observatory between 1945 and 1965. These data could be retrieved from the Brown University archives and more extensively analyzed.
3. The Navy makes a common practice of logging the time of sunset and weather conditions. The observations are recorded in paper rather than electronic format and maintained for a few years. These data may be useful and would give an excellent sampling of the conditions for which high zenith distance refraction is of interest. But they may not be sufficiently accurate to be useful enough to warrant the effort required to locate them and convert to an electronic format.

Retrieving either of these two possible caches of pre-existing data would be much less costly than a

concerted effort to acquire new data. So an effort should first be made to retrieve and examine this data before making a significant effort to obtain new data. If these data are available and useful, the most likely scenario is additional new data will still be required to reach the desired goals, but only a fraction of that required if the older data cannot be used.

A pilot project could be established to determine if the shipboard data of sunset times is of sufficient quality to be useful. Expert personnel would require access to the logged data from a typical deployment. In addition to the time of sunset, and similar astronomical observations such as the times of sunrise, moonrise, or moonset, the data required would be:

- the vessel’s location,
- the air pressure,
- the temperature at the observer,
- the observer’s height above the sea surface, and, either
 - the water temperature or
 - the air temperature at a location between the observer and the sea surface.

The humidity at the time of observation would also be useful, but is not critical. Evaluation of these data for sufficient quality should be quick requiring no more than a man-week of effort.

7. Summary

The determination of the refraction angle at high zenith distances is similar to the determination of the Earth orientation. The exact value at a given space-time coordinate is the result of unpredictable stochastic events. However, its value can be predicted for a significant period near the desired coordinate. The accuracy of that prediction decreases with distance from that coordinate. Two inferences of this analysis are: The current methods of prediction are nowhere near the limit of predictability, and the predictions can be significantly improved with a modicum of additional data on local atmospheric conditions near the time period of interest.

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