On the beginning of the morning twilight based on sky brightness measurements

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Abstract. We present the results of 83 measurements of night sky brightness with portable photometers for five locations, namely the Bosscha Observatory, Cimahi, Bandung, Yogyakarta, and Kupang during the moonless days from years 2011 to 2018. In the first place, instead of the zenith direction, we also evaluated the night sky brightness in various angles of the zenith distances. At the beginning of the morning twilight, solar dips were significantly affected by light and air pollution. It can cause a pseudo night effect, resulting from absorption by particles of low atmospheric height, which is due to air pollution. The duration of twilight is also influenced by the pollution level. A new tool to determine the boundaries of astronomical, nautical, and civil twilight using sky brightness difference was introduced. We also recommend a preferred solar dip of 18.5° for Islamic fajr prayer in Indonesia with twilight duration at 70.5 minutes.

1. Introduction
The rotation of the Earth or other planets towards its axis causes the transition day and night (twilight), in the form of dawn and dusk, in addition to the phenomenon of rising and descent of celestial objects. These three types of daily solar motion phenomena have been known since the beginning of human civilization. Twilight is a transition period from night to daytime or vice-versa. In one day, the surface of the Earth experiencing day around 42-45%, while the night covers 33-35%. As for the transition area, the day-night shift is 20-25%. Complexity occurs because twilight (at dawn and dusk) time is very sensitive depending on the atmosphere or the thin air layer enveloping the planet. The thickness, pressure, density, temperature, or chemical composition parameters vary with height so that unique atmospheric chemical and physical processes occur for each height of the atmosphere. Different distances to the Sun for seasonal motion also cause the process of interaction of light or energy of the Sun with the layers of the atmosphere also fluctuate [1]. Moreover, a significant contribution of man-made sources of particulate matter is generated from a variety of human activities that can absorb sunlight [2] and affect twilight duration because of molecular multiple scattering, extinction by tropospheric aerosols, and absorption by ozone [3].

For one location on the surface of the Earth, morning twilight is defined as the time that starts from the position of the Sun still below the horizon, but the sun's light begins to be scattered by the Earth's atmosphere until the sun rises. The reverse process for evening twilight, which is the time that starts from the sunset. The light multiple scattering processes cause the colors of dawn or dusk. The physical appearance of twilight is not as easy to see and feel as senses like the phenomenon of brighter sky
during the sun rising or setting. The beginning of morning twilight is more difficult to understand visually because the atmosphere is dark and the eyes are not sensitive to see any changes in light intensity and elusive color changes, so it requires tools to measure the multiple scattering of light and its color. The light meter instruments have to differentiate both from natural light sources and light pollution (man-made sky glow). It can also measure the height of the atmospheric structure of the layer and the composition that is not homogeneous. The impact of air pollution will be proportional to the light pollution which is due to the waste of upward city lights that can cause the sky brighter than natural conditions. Light pollution should be recognized as a disruption to our environment and our health [4]. It is not only a problem for astronomers, so it is also noted as a public health hazard and affecting daily religious worshipping.

The duration of dawn or dusk in the equator is around 1 hour 8 minutes to 1 hour 16 minutes. In locations with high latitudes, the duration reaches an order of several hours [5]. The sky color is more difficult to determine because it depends on meteorological conditions, surface topography, moon phases, or lower atmospheric aerosols chemical composition, if there are volcanic eruptions, forest fires or pollutant particles from industry and transportation.

The worship of Muslims is not only determined by the position and appearance of the two celestial objects of the Sun and Moon but also depends on the thickness and composition of the Earth's atmosphere with the interaction of complex light traces of refraction of sunlight, namely at dawn and dusk. The initial reference for the beginning of morning twilight (dawn) varies from country to country, due to the use of different solar elevation angles, between -15° to -20°. For the territory of Indonesia, the determination of the initial dawn time is still in the form of a collective agreement, namely elevation of -20°, so a re-analysis work needs to be done to provide and support for the observation database, as well as an effort to learn about the complexity of natural phenomena.

This paper is aimed to determine the solar dip of the beginning of morning twilight, duration to sunrise, and estimate the height of the atmosphere based on observing the brightness of the sky through a photometer. Observation data for sky brightness measurements comes from five locations with different altitudes above sea level from years 2011 to 2018.

2. Methods and results

2.1. Sky Quality Meter

To find out the changes in the brightness of the sky quickly and accurately needed a photometer or a measure of the brightness fluctuation of the light. This equipment is easy to find and use because it is widely sold in camera, photography, or physics laboratory outlets. For this research, a portable photometer is used, lightweight, and has a USB connection, so that it is easily connected and accessed to a computer. It is the Unihedron Sky Quality Meter (SQM). This photometer has a lens and a CM500 HOYA filter, with a spectral range between 300-720 nm (peak at 500 nm). Thus, the SQM detector response is the same as the visual spectral sensitivity of the human eye. The output of this unit is a calibrated amount of sky brightness (magnitude per second of arc square - mpsas), where a high value reflects the darkening sky. The magnitude of the brightness of the sky can be converted into units of candela (candles) per unit area or illumination. The other most important aspect, this photometer needs to be supported by software, so that it is able to work independently recording the brightness of the sky in a time lag every second from sunset to sunrise again. SQM can be used easily to get the quality of the night sky. The measurement angle is 20° and has temperature stability and noise value for sky brightness [6,7,8]. In this study, the time interval for data collection was 3-5 seconds. This photometer is directed perpendicular to the zenith. This photometer has been used for several previous studies [9,10,11,12].

Night sky brightness data were collected for five locations, namely Amfoang, Kupang, East Nusa Tenggara (124° 0' E; 9° 40' S; elevation 1300 m), Sleman, Yogyakarta (110° 25' E; 7° 52' S; elevation 100 m), Bosscha Observatory, West Java (107° 37' E; 6° 49' S; elevation 1300 m), Bandung (107° 36’ E; 6° 53’ S; elevation 781 m), and Cimahi, West Java (107° 32’ E; 6° 53’ S; elevation 700 m). Then,
the selection criteria for the day was in the new moon phase for years 2011 to 2018. We have 83 records of data. The mean brightness is computed for 3 hours from 0 to 3 AM. Figure 1 shows the morning sky brightness for five locations on selected dates.

Figure 1 shows the brightness of the sky as a function of the local time. The brightness profile of the night sky indicates the condition of the level of light pollution and air pollution. The sky in Kupang is the darkest sky, compared to the other three locations. Sky brightness values above 21 mpsas indicate that the Milky Way Galaxy can easily be seen directly by the eye. In contrast, the appearance of the Milky Way Galaxy is difficult to see in Cimahi and Yogyakarta. The Amfoang area, Kupang shows the lowest level of pollution, while the location with the worst pollution is in the Cimahi area. The Zodiac's light is not visible from the brightness patterns of the sky or recording visual photos in Kupang (as the darkest location), possibly due to SQM which leads to the zenith. In addition, the Zodiac light is very dim (about 1% difference with background brightness or about 0.2 mpsas), so to see it requires a darkest background brightness as possible in the direction of the horizon. So, in general, the Zodiac light is not visible at all locations.

The effect of light pollution is clearly seen in the Cimahi and Bandung areas. The beginning of the decline in the brightness value of the sky depends on the location. The location in Cimahi, despite having the most severe levels of light pollution, but in the nautical and civil twilight, there was a bright shift in the sky which was darker than Kupang. This is caused by higher levels of air pollution in Cimahi and Bandung, or in general in the Bandung Basin and surrounding areas, with quite large pollutant particles (> 10μm) originating from industry, motor vehicles, land burning, etc. [13,14], so that the light is not only scattered or refracted but instead absorbed by these particles and the sky is relatively darker for a longer time or called pseudo night. The pseudo-night effect is the condition of small changes in the brightness of the sky, due to sunlight absorbed by pollutant particles originating from air pollution that accumulates in the lower atmosphere (tropospheric layer).

2.2. Sun elevation angle and atmosphere height

The elevation angle of the Sun or solar dip as a function with time is obtained based on the formulation given by Meuss [15]. The effects of atmospheric refraction depend on the local conditions of the parameters of atmospheric pressure, humidity, temperature, etc. so the results of calculating the elevation angle and position of the Sun are simplified with low accuracy which is enough for this purpose. The moving average of two minutes from differences or gradients in brightness data was obtained. See figure 2. The night is quantified by zero brightness differences with 3-5 second interval time. Then, a curve fitting at 1.5 hours window time was performed to know the inflection of the time at the end of the night or the beginning of morning twilight. The inflection point is converted from time to solar dip in the degree unit.
The brightness difference or gradient curve was not as smooth as the brightness line. The cloud passages and haze of varying sizes could be sensitively recorded by SQM with high temporal resolution. Their existence leads to increasing sky brightness. In figure 2, the sky was clear and stable from 1.5 AM until the end of the night at about 4.6 AM. The elevation angle of the Sun at the night is deeper than -20° or earlier than 4.4 AM, there is no fluctuation in the brightness of the sky or is said to be stable in night conditions. After the inflection angle and starting to the beginning of twilight, the sky becomes quickly brighter until the sunrise with a gradient of -0.92 in the brightness variations. However, the increasing brightness is due to a nonlinear atmospheric phenomenon. This can be seen in brightness difference curves (right panel of figure 2). The skylight scattered in different height and thickness of the atmosphere, so SQM received the light with different rates for each layer. We define a new physical boundary in twilight classification based on their changing brightness that consists of astronomical, nautical and civil twilight. Each has a different rate. The increasing brightness rate in the astronomical twilight with a slope value of 0.003 is larger than the nautical slope of 0.002. The hump shape during nautical twilight could be related to density enhancement by shear flow with relation of $\frac{d \log I}{d \log h} \sim \frac{d \log n}{d \log h}$. The civil twilight is about the same gradient as astronomical twilight at a decreasing rate. Moreover, there is a turning point at 5.4 AM or at the beginning of civil twilight with 6° solar dip. All five locations have relatively similar patterns in the civil twilight period, but hump shape disappears at intense air pollution sites.

2.3 Inflection point
The inflection point of the beginning of morning twilight can be represented as a solar dip in the unit of degree. From the amount of 83 data during moonless nights, the darker value of mean brightness correlates with a deeper solar dip and has a linear slope with a value of 0.80±0.11 (seen as the central line in figure 3a). We added data from the other two sites at Labuan Bajo on 24 April 2018 [17] and Tayu from 31 August to 3 September 2016 [18] that can be compared with Kupang area for the dark
sky regions. The distribution of all data is within ±1σ errors of the linear regression, represented as upper and lower lines. The interpretation of these lines denotes the best and the worst atmospheric transparency. The upper limit of solar dip for the beginning of morning twilight from sites of the darkest pristine sky with 22.5 mpsas and city with heavy light pollution with 15 mpsas is 20.77° and 14.35°, respectively. The upper limit presumes for the best quality of seeing at one site. However, it is difficult to find the best site as dark as 22.5 mpsas in Indonesia. Bosscha Observatory has a broad range of bad to good seeing qualities. Although Labuan Bajo and Tayu sites are near the sea level, they can be regarded as the ideal transparency condition of Bosscha Observatory, since they have the same mean brightness level. The solar dip does not depend on altitude up to 1300 m above sea level at the highest altitude of data below low clouds at 2000 m. Observations at higher places, e.g. >2000 m should be performed to confirm this finding. The association of atmospheric height with morning mean brightness and solar dip is presented in figure 3b dan 3c. As expected, the sunlight for the early morning twilight initially interacts at higher altitudes for the darker sites with good transparency. The relation of top of atmospheric height, h and solar dip, A follows a square power law as

$$h = cA^2 (R^2=1)$$  \hspace{1cm} (2)

In figure 3d, the linear relation of solar dip and duration of twilight, t (time between the inflection point and sunrise) is shown as

$$A = 0.211±0.009 t + 3.681±0.539 (R^2=0.86)$$  \hspace{1cm} (3)

The duration of twilight larger than 1 hour could be reached at solar dip at least 16.3°. Typical twilight durations at solar dip 18°, 20°, and 22° take 68, 77.5 and 87 minutes, respectively.

The Indonesian archipelago consists of many large/small islands with very long coastlines, many narrow straits control the global (Pacific to Indian) ocean circulation, and the land-sea heat capacity contrasts along the coastlines generate the world's largest rainfall with diurnal cycles (sea-land breeze circulations). The diurnal cycles are dominant and lead to rapid land/hydrosphere-atmosphere water exchange, local air pollutant washout, and trans-equatorial boreal winter monsoon (cold surge) [19]. Most regions in Indonesia with an average elevation of less than 400 m above sea level will experience diurnal cloudy skies with yearly clear skies fraction less than 65% [20]. The cloud coverage conclusively magnifies the sky’s brightness. A solar dip in Islamic Fajr prayers from the official Indonesian government makes use of a consensus at 20° with a duration of about 77 minutes before sunrise. This angle is also used for the start of the time for fasting. The above results and climatology reasons give some limitations for the excellent sky brightness and atmospheric clarity levels of having at least 21.5 mpsas to obtain a 20° solar dip at certain sites. The pseudo night effect due to the combination of air and light pollution will cause brighter skies, lower solar dips, and shorter twilight duration, which are typical for urban areas. The solar dip could subsequently be revealed at a lower than 20°. From figure 3a, solar dips between 17° and 18.5° with twilight duration at 63 and 70.5 minutes and corresponds to 20.5 and 22.5 mpsas of sky brightness, respectively could be proposed as an actual solar dip for Islamic Fajr prayers in Indonesia.

In figure 4a, solar dips at 45° directions are the same as zenith, since SQM covers 20° field of view. The north-south directions show brighter sky than east-west due to more intense light pollution. Bandung city in south direction at about 10 km in distance becomes a significant source of light pollution above Bosscha Observatory. Figure 4b shows the sky brightness as it functions with the zenith distance in the south direction (azimuth 135°-225°) from Bosscha Observatory on October 10, 2018. The city sky glow affects larger than 40° of the zenith distances, makes smaller observing window, and hide patch of Milky way galaxy. The light pollution problem could reach to stratospheric layer. Based on observations of LiDAR (Light Detection and Ranging) in the area of Bandung, aerosols in the stratosphere layer are at an altitude of 18-35 km. Aerosol density concentrations and temperature inversion layers occur at an altitude of about 16 km and 23 km, respectively [21,22].
Because each layer of the atmosphere has different characteristics, causing a complex scattering and refraction process, more precise equipment is needed to determine the vertical profile of the atmosphere using a combination of Raman and Rayleigh LiDAR, and imaging photometer equipment for simultaneous observation with high temporal resolution.

Figure 3. (a-top left) Distribution of mean brightness from 0 to 3 AM with solar depression at the beginning of morning twilight and (b-top right) with atmospheric height; (c-bottom left) relation of atmospheric height with solar dip, and (d-bottom right) relation of solar dip with twilight duration. Symbols of each site are the same as panel a. Solar dip is presented in positive values.

Figure 4. (a-left) The solar dip (presented as positive value) from a different direction with 45° angles at Bosscha Observatory; (b-right) sky brightness as a function with zenith distance in south direction with azimuth 135° - 225°.
3. Conclusions
Based on 83 moonless observations using a photometer with a recording interval time of every 3-5 seconds for five different locations altitude and level of light pollution, as well as air pollution, it can be concluded that

- The effects of light and air pollution have a strong influence on changes in the brightness of the sky, atmospheric transparency, solar dip, and twilight duration.
- A pseudo-night effect, due to the absorption of light by pollutant particles in the lower atmosphere, was observed for resulting in the late astronomical twilight.
- A new tool of brightness differences or gradients is introduced to define the boundaries of sky brightness of astronomical, nautical, and civil twilight.
- Solar dips at between 17° and 18.5° with twilight duration at 63 and 70.5 minutes, respectively, could be recommended as a suitable solar dip for Islamic Fajr prayers in Indonesia.

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