SST Illumination

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1 Purpose

This document outlines the rationale and justification for a new requirement on NSB illumination levels for SSTs. To increase the available observation time, it is envisaged to make further use of partial moonlight conditions and twilight conditions for observations. Currently, requirement A-PERF-0130 states that the performance under partial moonlight up to a level of 1.2 photons ns^{-1} sr^{-1} cm^{-2} should be less than a factor of two worse than the dark sky performance. However, it is envisaged that SSTs utilising SiPMs may be able to observe under brightness levels up to six times this level; i.e. up to 30 times the expectation for astronomical darkness. Hence a new requirement is proposed to ensure that SSTs will be able to operate under such conditions.

Values given here correspond to the visible (V) wavelength band; values for other wavelength bands (particularly U and B) were not found to deviate significantly.

2 NSB Illumination Levels

A typical NSB rate under astronomically dark conditions (sun $< 18°$ below the horizon, no moon) is approximately 22 mag/arcsec^2 in the visible wavelength band. For comparison, a particularly NSB bright region of the sky (e.g. the Eta Carinae region) may have an average NSB rate of $\sim$5 times this value on degree scales.

CTA should be able to conduct observations in all regions of the sky, regardless of NSB rate. Clearly some resilience to high levels of NSB brightness is desirable. A trade-off between increasing levels of NSB and increased observation time can be considered by not restricting observations to astronomically dark conditions only. Corresponding NSB levels for the cases of partial moonlight and for twilight conditions (sun $< 18°$ below the horizon) are outlined in sections 2.1 and 2.2 respectively.

2.1 Partial Moonlight

As defined by ESO for the Paranal site, Moon illumination (fraction of lunar illumination, FLI) is the fraction of the lunar disk that is illuminated at local civil midnight. i.e. 0 when the moon is below the horizon and 1.0 at full moon. Lunar **dark time** corresponds to FLI < 0.4; lunar **grey time** corresponds to $0.4 <$ FLI < 0.7 and a minimum angular distance of $90°$ or less between the moon and observation target [1]. The boundaries between lunar dark time and lunar grey time, as defined by ESO in the context of the Paranal site, may need to be adjusted to suit the needs of CTA and for the La Palma site.

For increases in NSB brightness of up to a factor of 5-6 times that of astronomical darkness (as currently required), it is estimated that observations can continue with the moon above the horizon for ~ 6 nights either side of new moon. An example of the relevant increase in NSB brightness with moon phase is given in table 2.1. These values are derived under the assumption of a target at $30°$ zenith angle, separated by $70°$ from the moon at $45°$ zenith angle [3].

Days since new moon	FLI	NSB (mag/arcsec^2)	Brightness Increase
0	0	22.05	-
5	0.266	20.74	3.34
10	0.781	18.71	21.68
14	0.997	17.06	99.08

Table 2.1 – Illustrative brightness increase for NSB in the V band with moon phase (days since new moon).

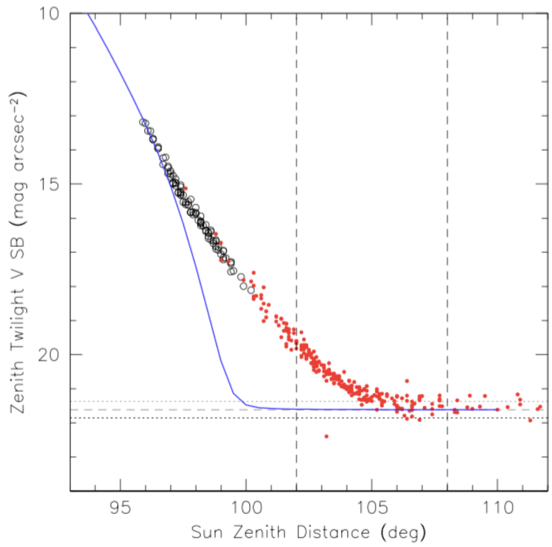

Figure 2.1 – Sky brightness in the V band as a function of the solar zenith angle. The blue curve is a simple model, whilst the points correspond to data from ESO at Paranal. Horizontal lines mark the average dark-time NSB level at Paranal (and 1σ deviations). Vertical lines mark the end of nautical ($102°$) and astronomical ($108°$) twilight respectively.

Whilst there is some variation in NSB brightness between sites and depending on the relative positions of the moon and target on the sky, the NSB remains within a factor of $\sim$5 of astronomically dark conditions even with the moon above the horizon for a period of around 10 days each lunar cycle. Within this time period, continuing observations are expected.

Assuming that SSTs with SiPMs can withstand a factor 30 increase in NSB over astronomically dark conditions, a factor of 5-6 over the current requirement, then an additional 11 nights either side of new moon may be utilised.

2.2 Twilight Conditions

The following definitions are usually used for twilight conditions:

- Astronomical twilight: sun is between 12° and 18° below the horizon.
- Nautical twilight: sun is between 6° and 12° below the horizon.
- Civil twilight: sun is between 0.83° (0°50') and 6° below the horizon.

Figure 2.1, taken from [2], illustrates the increase in sky brightness with zenith angle of the sun for the V wavelength band.[1]

From figure 2.1 and complementary figures in [2], it is estimated that observations can continue under dark time conditions whilst the sun is at least $-17°$ below the horizon. Observations may continue

[1] Similar plots for the UBRI bands may also be found in [2].

days since new moon	FLI	Hours at Paranal		Hours at La Palma	
		sun $< -18°$	sun $< -15°$	sun $< -18°$	sun $< -15°$
0	0	1593	1675	1564	1650
5	0.266	1731	1834	1697	1804
10	0.781	2397	2530	2352	2491
14	0.997	3272	3440	3221	3397

Table 2.2 – Altitude of the sun below the horizon and the corresponding total number of hours per year fulfilling both solar elevation and FLI less than that listed in each row.

under grey time conditions whilst the sun is between $-14° - -15°$ and $-17°$ below the horizon. Higher elevations (up to $\sim -12°$) may also be possible, however the sky brightness will be changing rapidly during this time.

Table 2.2 lists the number of hours per year fulfilling the conditions of FLI $\leq$ the FLI in each row, and of solar elevation angle $\leq$ that given, for both Paranal and La Palma.

To consolidate table 2.2, under strict astronomical darkness conditions, at Paranal, 1593 hours (1564 hours at La Palma) are available for observations each year, whereas by relaxing the solar elevation requirement to $< -15°$ results in 1675 (1650) hours per year, a $\sim 5\%$ increase. Combining this with a factor 5 increase in NSB, roughly covering 6 nights either side of new moon with the moon above the horizon, this results in 1941 (1909) hours per year, a $\sim 22\%$ increase. If an additional factor 30 increase in NSB is permitted, observations may continue for up to 11 nights either side of new moon, resulting in (roughly) 2743 (2698) hours per year, a $\sim 70\%$ increase over strictly dark time only.

3 Proposed Requirement

The proposed new requirement is:

SSTs must be capable of gamma-ray observations at night sky background illumination levels up to at least 7 photons ns^{-1} sr^{-1} cm^{-2} in the wavelength range 300-650 nm, approximately 30 times the illumination level expected for astronomical darkness.

The same requirement is proposed also for SCTs.

4 Conclusion

The increase in observation times provided by conducting observations under partial moonlight and twilight conditions up to a factor of 30 times brighter than astronomical darkness leads to a cumulative difference of ~ 95 hours per month, 1150 per year, and potentially 34500 over the projected 30 lifetime of CTA, effectively adding another 12.5 years worth of observations. It is felt that this more than justifies raising the required NSB level to 7 photons ns^{-1} sr^{-1} cm^{-2} for SSTs and SCTs if technically possible, as these increased hours could be of decisive importance in the detection of flaring sources or in the case of ToO alerts (for example).

We note that it is intended to translate part of the material in this note in to a new document defining illumination levels for CTA is an input to the proposal executation / scheduling process.

References

[1] Observing Conditions: definitions, European Southern Observatory `https://www.eso.org/sci/observing/phase2/ObsConditions.SINFONI.html` *Accessed XX/10/2016*

[2] F. Patat, O. S. Ugolnikov and O. V. Postylyakov, *UBVRI twilight sky brightness at ESO-Paranal* Astronomy and Astrophysics, **455**, 385-393 (2006)

[3] K. Krisciunas and B. E. Schaefer, *A Model of the Brightness of Moonlight*, PASP **103**, 1033-1039 (1991)