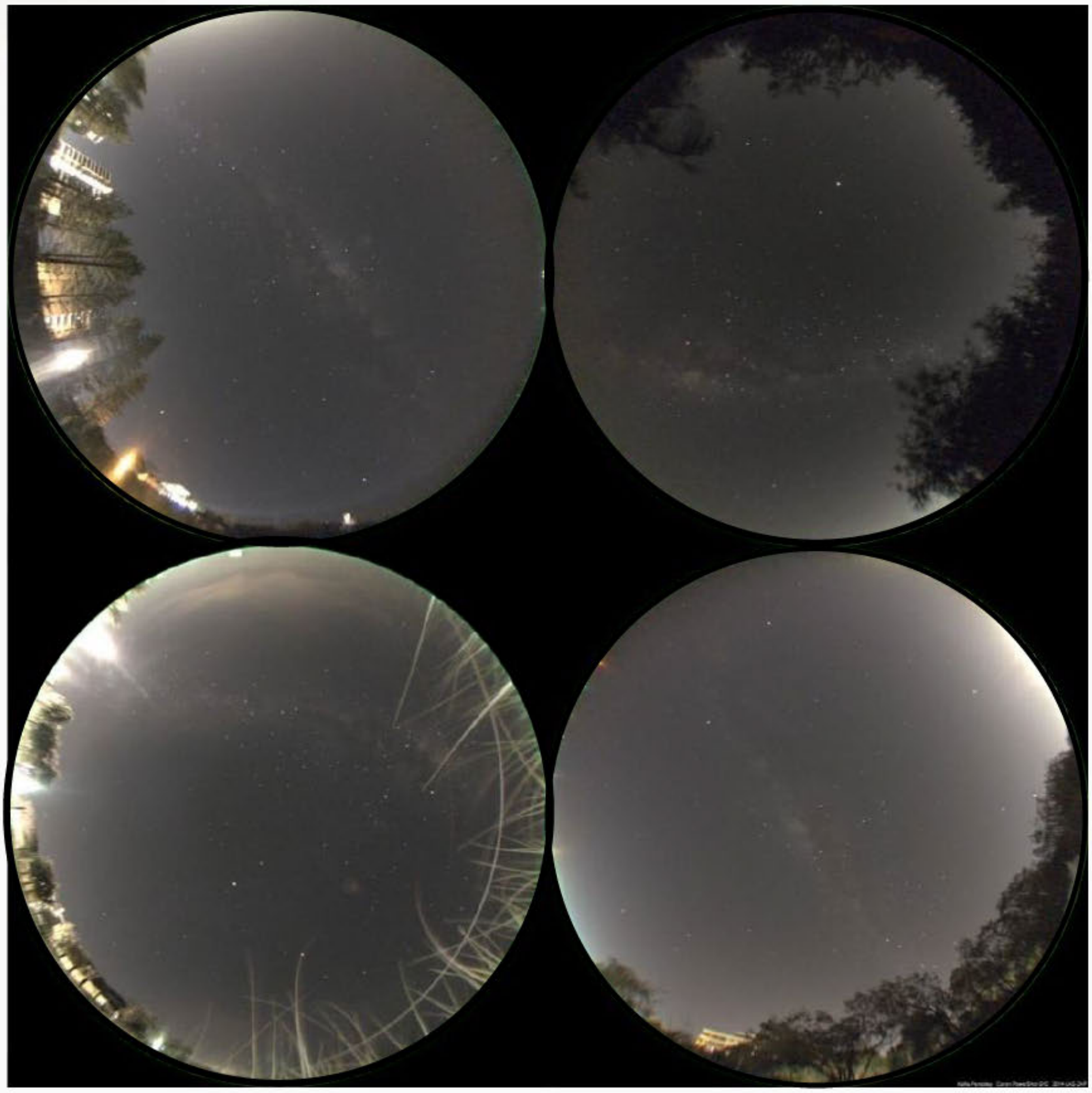
# SUNSHINE COAST AND MORETON BAY REGIONAL COUNCIL

# BENCHMARK ARTIFICIAL LIGHT AT NIGHT (ALAN) SURVEY 2017



Prepared in July 2017 by

Pendoley Environmental Pty Ltd for

Sunshine Coast Council & Moreton Bay Regional Council

PENDOLEY ENVIRONMENTAL

MARINE CONSERVATION
ENVIRONMENTAL SERVICES

# DOCUMENT CONTROL INFORMATION

## TITLE: ARTIFICIAL LIGHT AT NIGHT (ALAN) BENCHMARK SURVEYS 2017



### Document History

| Revision | Description | Date received | Date issued | Personnel |
|---|---|---|---|---|
| Draft | Report Draft | | 11/09/2017 | Dr C Bell |
| Rev IA | Internal Review | 11/09/2017 | 12/09/2017 | Dr K Pendoley |
| Rev A | Client review | 14/09/2017 | 10/10/2017 | K Hofmeister/ A Evans |
| Rev B | Incorporate Client Comments | 10/10/2017 | 27/10/2017 | K Pendoley / C Bell / A Mitchell |
| Rev 0 | Final report issued | 07/11/2017 | 07/11/2017 | K Pendoley / C Bell / A Mitchell |
| Rev 1 | Peer Review of Rev 0 | 18/01/2018 | 19/01/2018 | P Hick/ K Pendoley/ C Bell |
| Rev 2 | Corrected Mudjimba GPS | 02/07/2020 | 02/07/2020 | A Mitchell |

| | |
|---|---|
| Printed: | 19 January 2018 18:43 |
| Last saved: | 19 January 2018 18:36 |
| File name: | P:\06 Projects\J53 Sunshine Coast\J53001 Sunshine coast ALAN Survey\05 Programs\J53001-Sunshine Coast ALAN\05 Technical Reports\RP-J53001-SunshineCoast__BenchmarkALANSurvey_Rev1.docx |
| Author(s): | Dr Catherine Bell/K Pendoley/A Mitchell |
| Project manager: | Dr Catherine Bell |
| Name of organisation: | Pendoley Environmental Pty Ltd |
| Name of project: | Sunshine Coast Benchmark (ALAN) Survey 2017 |
| Client | Sunshine Coast Council/Moreton Bay Regional Council |
| Client representative: | Kate Hofmeister/Andrew Evans |
| Report number: | J53001 (J55001) |
| Cover photo: | Catherine Bell/Hugh Osborn |

## EXECUTIVE SUMMARY

Artificial light at night (ALAN) associated with human development is an emerging threat to a wide range of taxa worldwide. Modification of ambient light levels and changes to the night sky horizon have the potential to cause a decline in successful marine turtle nesting and disrupt ocean-finding in emergent hatchlings. The beaches of the Sunshine Coast and South Bribie Island support habitat critical to the survival of loggerhead turtles (*Caretta caretta*) which are the predominant nesting species, and green (*Chelonia mydas*) turtles, which nest in smaller numbers.

Hatchlings follow three primary cues when sea-finding; movement toward brighter regions on the horizon, movement away from tall dark beach silhouettes (e.g. dunes and tree lines) and when these cues are inconsistent, movement in relation to elevation (Bartol & Musick 2003; Limpus 1971; Salmon et al. 1992; Limpus & Kamrowski 2013; Pendoley & Kamrowski 2015). Therefore, artificial light is one of several competitive visual stimuli that hatchlings must integrate with natural light intensity, wavelength, directivity, and horizon/elevation cues to navigate successfully toward the ocean.

The main objective of the study was to establish, on behalf of the Sunshine Coast Council and the Moreton Bay Regional Council, a benchmark for current light emission levels. With this information, future variation in night sky brightness can be meaningfully evaluated. Findings can be used to inform strategic planning decisions, monitor trends and work towards targets within the Urban Lighting Master Plan (ULMP); assess development proposals and facilitate useful mitigation of current and future light emissions, particularly in the vicinity of marine turtle nesting habitat.

Using Sky42™ technology, images of the night sky were gathered over three survey nights at each of 16 monitoring sites (Sunshine Coast: $n$ = 13; South Bribie Island: $n$ = 3) during the new moon phase in June 2017. Up to five images were taken at each site and one selected for analysis based on multiple criteria detailed within. Sky brightness, measured in units of magnitudes/arcsec$^2$, was quantified for three sky sections: horizon, zenith and whole of sky. Images taken on clear, cloudless nights are used for comparative purposes; cloudy sky images are used to demonstrate the effect cloud cover has on night sky brightness. Cloud cover has many, variable qualities and therefore brightness was subject to substantial variation depending on cloud height, thickness, density, coverage and type.

Horizon brightness was greatest at Woorim beach (mid), Buddina (Coopers Lookout/Kawana SLSC) Mooloolaba, Mudjimba (south) and Coolum (south) and was dimmest at Woorim beach (north), Woorim beach (south) and Yaroomba (north). Zenith, or overhead brightness was greatest at Buddina (Coopers Lookout/Kawana SLSC), Mooloolaba and Coolum (south) and dimmest at Woorim beach (south and north), North Bribie Island and Yaroomba (south and north). Whole of sky brightness was greatest at Buddina (Coopers Lookout/Kawana SLSC), Mooloolaba and Coolum (south) and dimmest at Woorim beach (south and north), North Bribie Island and Yaroomba (south and north).

The primary source of sky glow at all locations was towns and cities located along the coastline. Specifically, glow from Brisbane, was visible from Bribie Island and Caloundra and is likely to be contributing to the sky glow visible from beaches along the Sunshine Coast albeit at lower intensity levels than more localised light sources.

Additional glow from infrastructure e.g. roads and street lights, light industrial and commercial facilities e.g. sports grounds, unique facilities e.g. Sunshine Coast Airport and temporary sources e.g.

State Government Transport Main Roads roadworks project contributed cumulatively to overall glow in the night sky.

The extended urban zone between Pelican Waters in the south and Mooloolaba in the north cumulatively contributes a substantial amount of light to the sky glow over the Sunshine coast which is detectable from the southern end of Bribie Island in the south to Coolum in the north. On a local scale, street light and most commonly, car park lighting, increased brightness substantially where fixtures were located adjacent to the nesting beach. There were no offshore sources of lighting detected in this survey.

At Coopers Lookout/Kawana SLSC in Buddina, a trial to quantify emission variation under different lighting scenarios measured brightness with a. the newly installed LED lights in the carpark switched off and all other lighting remaining on and b. all carpark lights, new and old, switched off and only lights at the SLSC and public facilities (toilets) switched on. The objective was to obtain information to understand the contribution of emissions from the new LED lights to sky glow. Results showed a decrease in brightness in scenario b., compared to a. (when the new LED lights were switched off) and little change when the old carpark lights were also switched off. We conclude the new carpark lights are brighter than the old carpark lights and make recommendations for future surveys to include controlled studies to explore this further.

A lighting audit identified 24 individual lighting fixtures on four beaches with luminaires directly visible from the nesting beach that could be adjusted to decrease light reaching the beach. Of note were the newly installed LED fixtures at Coopers Lookout/Kawana SLSC. Bright white LED lights emit a high proportion of short wavelength blue light, the light that is most attractive to marine turtle hatchlings. Short wavelength light is strongly scattered and reflected in the night sky. Amber LED light however, is a monochromatic light emitting at ~590 nm. It is strongly recommended that shielded amber LED lights are used in the vicinity of marine turtle nesting habitat.

In all instances, the presence of cloud increased sky brightness and where low heavy cloud intersected brightly lit areas the increase in sky glow was greatest (e.g. Buddina Coopers Lookout/Kawana SLSC with LED lights on and Mooloolaba, cloudy sky). This increase in sky brightness increased the visibility of sky glow on the horizon where clouds were located above a geographically remote light source. For example the lights of Brisbane are visible on the horizon from Bribie Island when there are clouds over Brisbane reflecting the light back to the earth.

Two primary, yet manageable features were recognised as decreasing night sky quality were inappropriately positioned and poorly managed lighting located adjacent to the nesting beach (typically carpark, street and public facility lighting), and the use of bright, white LED light fixtures.

Four specific topographical, ecological and structural features were identified that support hatchling sea-finding:

- Vegetation screening: on the dune line at 12 of 16 monitored sites, created sections of tall dark horizon for hatchlings to use as a cue in sea-finding;
- Cliff elevation: where present, provided hatchlings with a dark horizon to orient toward;

- Lighting design and management: at specific locations, which could easily be modified to reduce emissions and overall sky glow with small changes to fixtures, such as changing the lamp type and wattage or adding shielding and changing the orientation of the fixture; and
- Building orientation: being angled away from the nesting beach such that light did not spill onto the sand.

Building orientation at Point Cartwright, where apartments/units were built facing to the west, looking over the marina and away from the beach, in combination with topographical elevation (high cliff line, tall tree line), means little light from the units is directly visible from the beach. Visible light on this beach originates largely from carpark and public lighting located along the walkways, pathways and at the toilet block above the monitoring site.

The importance of vegetation at the nesting beach cannot be over stated. With climate change expected to drive changes in habitat conditions, warmer temperatures will expand the current nesting range of turtle populations focused around rookeries further north into the Sunshine Coast region. Planting trees and vegetation and maintaining existing vegetation screens is critical to the maintenance of suitable nesting habitat. Trees shield the beach from light, supporting adult nesting and providing a tall, dark horizon cue against which hatchlings can orient themselves toward the ocean. Vegetation will also stabilize the dune profile providing protection from rising sea levels and modified tidal systems and provide shading, cooling sand temperatures to minimise the potential impacts of temperature change on sex-ratios.

This regional light pollution monitoring program, using Sky42™ technology established 'benchmark' levels of night-time illumination visible from key marine turtle nesting beaches on the Sunshine Coast and Bribie Island in Queensland. The results provide information to, inform strategic planning decisions, meet specific targets within the ULMP, understand cumulative impacts of light on turtles, support effective management of light emissions at the beach and address concerns regarding LED lighting and reduce overall emissions. Future repetition of these surveys will allow detected variation in night time illumination to be quantified, assigned to source and, where problematic, reduced or removed.

# TABLE OF CONTENTS

## LIST OF FIGURES

## LIST OF TABLES



## LIST OF APPENDICES

# ACRONYMS & ABBREVIATIONS

| | |
|---|---|
| **ALAN** | Artificial Light at Night |
| **CCT** | Correlated Color Temperature |
| **Coopers / SLSC** | Coopers Lookout / Kawana SLSC |
| **DEHP** | Department of Environment and Heritage |
| **IDA** | International Dark Sky Association |
| **LGA** | Local Government Area |
| **mag / arcsec$^2$** | Astronomical units of luminance; a measure of the brightness of an extended area of sky |
| **MBRC** | Moreton Bay Regional Council |
| **PALM** | Permits and Licensing Management |
| **PENV** | Pendoley Environmental |
| **SCC** | Sunshine Coast Council |
| **Sky42™** | Custom technology developed in-house at PENV by Digital Horizon Imaging |
| **SLSC** | Surf Life Saving Club |
| **SQM** | Sky Quality Meter |
| **ULMP** | Urban Lighting Master Plan |
| **UNEP** | United Nations Environment Program |

# 1 INTRODUCTION

## 1.1 The Sunshine Coast and Moreton Bay

The Australian coastline is currently undergoing rapid development to meet the requirements of its expanding industrial, residential and tourism sectors, particularly notable along the Queensland coast (Australian Bureau of Statistics 2011; Grech et al. 2013). The Sunshine Coast in Queensland has a highly developed coastline, with a population density in 2016 of 134.6 people per square kilometre (Australian Bureau of Statistics 2017).

All living things on earth have evolved under millions of years of a 24 hour light-dark cycle. It is only in the past ~150 years that humans have been able to artificially extend light into the night, distorting the balance between light and dark. Artificial light at night (ALAN) associated with human development globally is an emerging threat to a wide range of taxa and specifically to adult and hatchlings marine turtles and to successful marine turtle nesting on Sunshine Coast beaches. Modification of ambient light levels and changes to the night sky horizon have the potential to cause a decline in adult turtle nesting behaviour and the disruption of ocean-finding in emergent hatchlings.

## 1.2 Project Background

All species of marine turtles in Australia are potentially exposed to levels of artificial light which can be considered 'light pollution' (Smith 1979; Kamrowski et al. 2012) - generally understood as an excess of artificial light at night (ALAN), which is increasing at around 6% per annum (Holker et al. 2010; Gaston et al. 2015). Levels of artificial lighting were recently found to be high and increasing significantly faster, at eastern Australian nesting beaches, relative to most other populations of turtles nationally, with some exceptions (Kamrowski et al. 2012; Kamrowski et al. 2014a)

The Council is obligated under the Environmental Protection and Biodiversity Conservation (EPBC) Act (1999) and the Commonwealth Marine Turtle Recovery Plan to protect habitat critical to the survival of marine turtles. The Plan is consistent with United Nations Environment Program (UNEP) Action Plan targets for the Loggerhead Turtle and the International Dark Sky Association conventions for the protection of the night sky and it is proposed therefore that management guidelines within the Plan are sufficient to afford the necessary protection to the local populations of nesting marine turtle and their habitat. The Sunshine Coast Council (SCC) has endorsed an Urban Public Lighting Master Plan (the 'Plan') (September 2016), which sets strategic guidance to support Council's vision to be the most sustainable region in Australia.

The coastline within the SCC Local Government Area (LGA) includes all nesting beaches from Coolum in the north to North Bribie Island in the south. Moreton Bay marine turtle nesting beaches are managed by Moreton Bay Regional Council (MBRC). These locations are shown in **Figures 1** and **2**. Sunshine Coast nesting beaches are monitored and managed by the SCC who coordinates 'TurtleCare Sunshine Coast' and supports 'Coolum and North Shore District Coast Care'. These community groups are responsible for monitoring marine turtle nesting activity and protecting marine turtle nests within the LGA. The location of all recorded nesting activity on the Sunshine Coast from 2008 – 2016 is shown in **Figure 1**. Marine turtle nesting beach on South Bribie Island are monitored by Bribie Island Turtle Care volunteers who supply nesting data to Moreton Bay Regional Council.

There is historical evidence of impacts of ALAN on adult and hatchling marine turtle behaviour in the region. Disoriented hatchling events were recorded at Shelly Beach, Dicky Beach, Buddina Beach and Stumers Creek, Coolum on the Sunshine Coast and at Queens Beach, Scarborough in Moreton Bay. Adult nesting behaviour has been affected at Mooloolaba and there are anecdotal reports of nesting adults being impacted by lighting on the beach adjacent to Rickman Parade, Woorim, in Moreton Bay

Under current building standards and lifestyle practices, night time illumination is predicted to increase along the coastline in conjunction with population growth and development expansion. The Sunshine Coast and Moreton Bay Regional Councils are responsible for assessment of new developments and modifications to existing developments within their respective LGAs.

## 1.3 Marine Turtle Populations of the Sunshine Coast and Moreton Bay Regions

The beaches of the Sunshine Coast support habitat critical to survival of loggerhead turtles (*Caretta caretta*) which are the predominant nesting species, and green (*Chelonia mydas*) turtles, which nest in smaller numbers. Although nesting numbers of both species are small compared to other nesting regions within Queensland (Limpus 2009), Australia's total annual population of nesting loggerheads in eastern Australia is made up of only approximately 500 females (Limpus & Limpus 2003), 5 % of which are known to nest on the Sunshine Coast. As a result the Sunshine Coast population is a small but important sub-population (Sunshine Coast Council 2013).

## 1.4 Marine Turtles and Artificial Light

Marine turtles have evolved to have two nocturnal stages in their critical breeding life history (Carr & Ogren 1960; Mrosovsky 1968; Limpus 1985; Gyuris 1993; Koch et al*.* 2008; Kamrowski et al. 2014b), which are sensitive to ambient lighting; adult nesting and hatchling sea-finding (Witherington & Martin 2000; Salmon 2003). Adult females will preferentially nest on darker beaches, meaning artificial lighting adjacent to the nesting beach can deter females from emerging to nest (Talbert et al. 1980; Salmon et al. 2000). In some cases, and dependent upon a range of natural and anthropogenic factors, artificial lighting has been shown to disrupt hatchling ability to locate the ocean after emerging from the nest in some cases because hatchlings use topographic and brightness cues for sea-finding (e.g. Mrosovsky & Shettleworth 1968; Salmon et al. 1992; Lohmann et al. 1997; Limpus & Kamrowski 2013; Pendoley & Kamrowski 2015).

Some documented examples of the impact of light on marine turtles in the Queensland region include Hodge et al. (2007), who examined tracks of adult females at a minor nesting beach on Hummock Hill Island (located ~29 km south of Gladstone, Queensland) and concluded that sky glow from the Gladstone region, up to 18 km distant, and lights from vessels at anchor outside Port Curtis, were contributing to disorientation in adult turtle nesting behaviour. Kamrowski et al. (2014b) examined tracks of emergent hatchling turtles at a nesting beach on Curtis Island in 2012/13 and concluded sky glow visible from the nesting beach was likely contributing to disruption in hatchling turtle sea-finding behaviour.

## 1.5 Scope of Work and Objectives

The SSC engaged Pendoley Environmental (PENV) to assess ALAN at selected nesting beaches along the coastline to provide a benchmark with which to assess current and future development plans in consideration of potential impacts to nesting and emerging hatchling marine turtles. An offer to collaborate was accepted by Moreton Bay Regional Council and survey sites within their LGA were included. The primary objective of this project was therefore to conduct a *Benchmark Artificial Light at Night Survey.*

The complete Scope of Works included:

a. Night-time surveys of ALAN at selected sites on monitored nesting beaches along the coastline;
b. A visual assessment of specific light sources visible from each nesting beach; and;
c. A report providing baseline information and describing location-specific and cumulative lighting impacts at multiple locations along the coastline known to provide important nesting habitat for marine turtles.

The specific objectives of this project were to:

- Establish a baseline or benchmark light emission level for use in assessment of development approvals, artificial light at night reduction and community education projects;
- Address cumulative impacts of light on marine turtles;
- Inform strategic planning decisions along the entire length of the Sunshine Coast Council coastline;
- Establish a reference and quantitative basis for future surveys in order for council to measure, monitor trends and work towards targets outlined within the Sunshine Coast Council Urban Lighting Master plan;
- Facilitate further discussion and planning about how to mitigate light emissions using the baseline information as a target, particularly in development codes, performance outcomes in the Sunshine Coast Planning Scheme; and
- Communicate the results of the survey to internal staff, community, consultants and elected representatives.

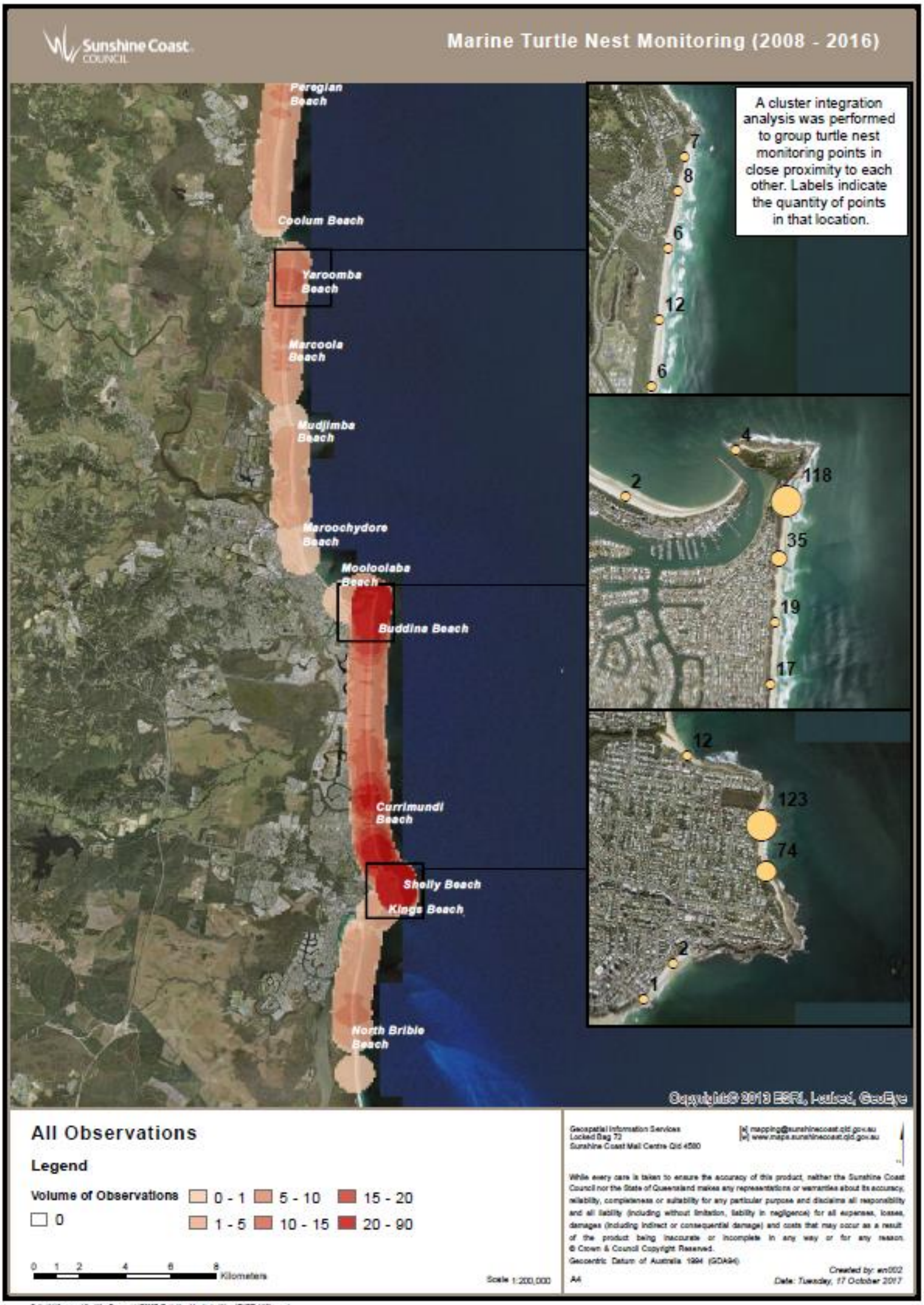



**Figure 1: Marine turtle nesting activity, Sunshine Coast 2008 - 2016.** Map supplied by Sunshine Coast Council.

# 2 METHODOLOGY

## 2.1 Survey Schedule and Approach

The survey methods have been developed by Pendoley Environmental over the past decade and are consistent with the research methodologies published by Falchi (2011) and Jerchow et al. (2017).

These surveys were conducted from 21st to 26th June 2017. Images were captured over three survey nights (21st, 22nd and 23rd June) at three monitoring sites on Woorim Beach, South Bribie Island (Moreton Bay Regional Council LGA) and three survey nights (24th, 25th and 26th June) at 13 monitoring sites on the Sunshine Coast (Sunshine Coast Council LGA) between North Bribie Island and Coolum (**Table 1**). See **Figures 2** and **3** for maps of the survey location and survey sites and **Appendix A** for maps of individual beaches showing position of each monitoring site location.

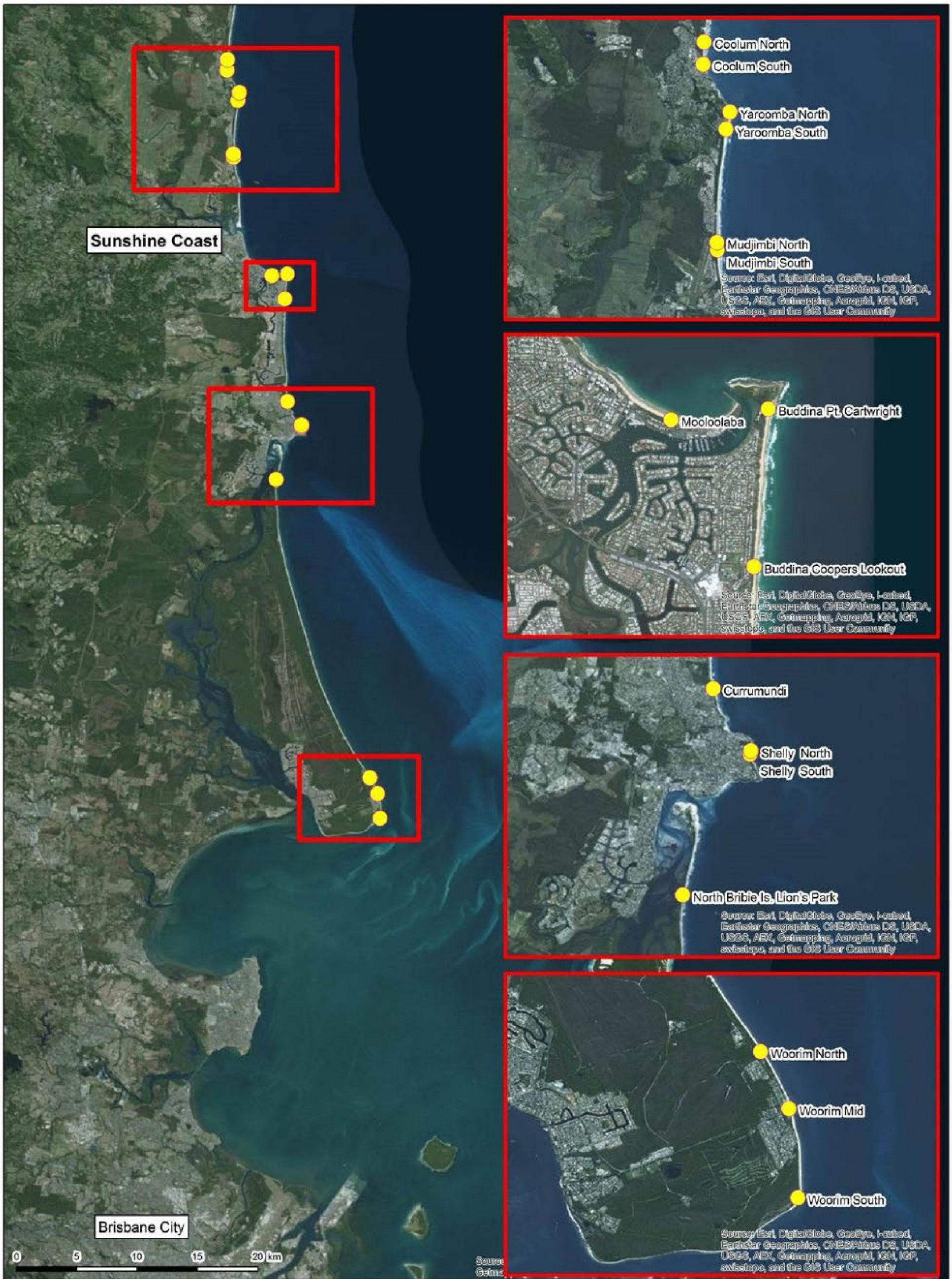
**Table 1: Survey dates and locations.** Light grey fill: clear sky images captured at this location on this date. Dark grey fill: images of clear and cloudy sky conditions captured; x: multiple images captured different lighting scenarios; Coopers/SLSC: Coopers Lookout/Kawana Surf Life Saving Club.

| Beach | Monitoring | 21st | 22nd | 23rd | 24th | 25th | 26th |
|---|---|---|---|---|---|---|---|
| South Bribie Is. | Woorim South | | | | | | |
| South Bribie Is. | Woorim Mid | | | | | | |
| South Bribie Is. | Woorim North | | | | | | |
| North Bribie Is. | Lion's Park | | | | | | |
| Shelly | South | | | | | | |
| Shelly | North | | | | | | |
| Currimundi | Currimundi | | | | | | |
| Buddina | Coopers / SLSC | | | | | x | |
| Buddina | Pt. Cartwright | | | | | | |
| Mooloolaba | Mooloolaba | | | | | | |
| Mudjimba | South | | | | | | |
| Mudjimba | North | | | | | | |
| Yaroomba | South | | | | | | |
| Yaroomba | North | | | | | | |
| Coolum | South | | | | | | |
| Coolum | North | | | | | | |

All monitoring sites were accessed by car via main roads with the exception of North Bribie Island which was accessed by boat. On each survey night, Sky42™ captured up to five images at approximately five minute intervals at each location (**Table 1**). At North Bribie Island, due to the logistical constraints of accessing the beach, Sky42™ was deployed prior to sunset, left to capture images overnight and collected after sunrise.

### 2.1.1 Lunar Phase

The relative brightness of artificial lighting fluctuates as a function of moon phase (Salmon & Witherington 1995; Pendoley 2005; Tuxbury & Salmon 2005; Berry et al. 2013; Kamrowski et al. 2014). Artificial light surveys are scheduled to occur during new moon conditions in order to isolate the effects of artificial light by reducing potential lunar interference.




J53001 Sunshine Coast ALAN Survey

**Figure 2: Overview of monitoring sites, Benchmark Artificial Light at Night Survey, 2017.**

Legend
ALAN Survey sites

N

Drawn: P. Becker
Date: 20/07/2017
Drawing File Ref:
PENV-J53001-831-A
Coordinate System: GDA 1994 MGA Zone 56

PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES

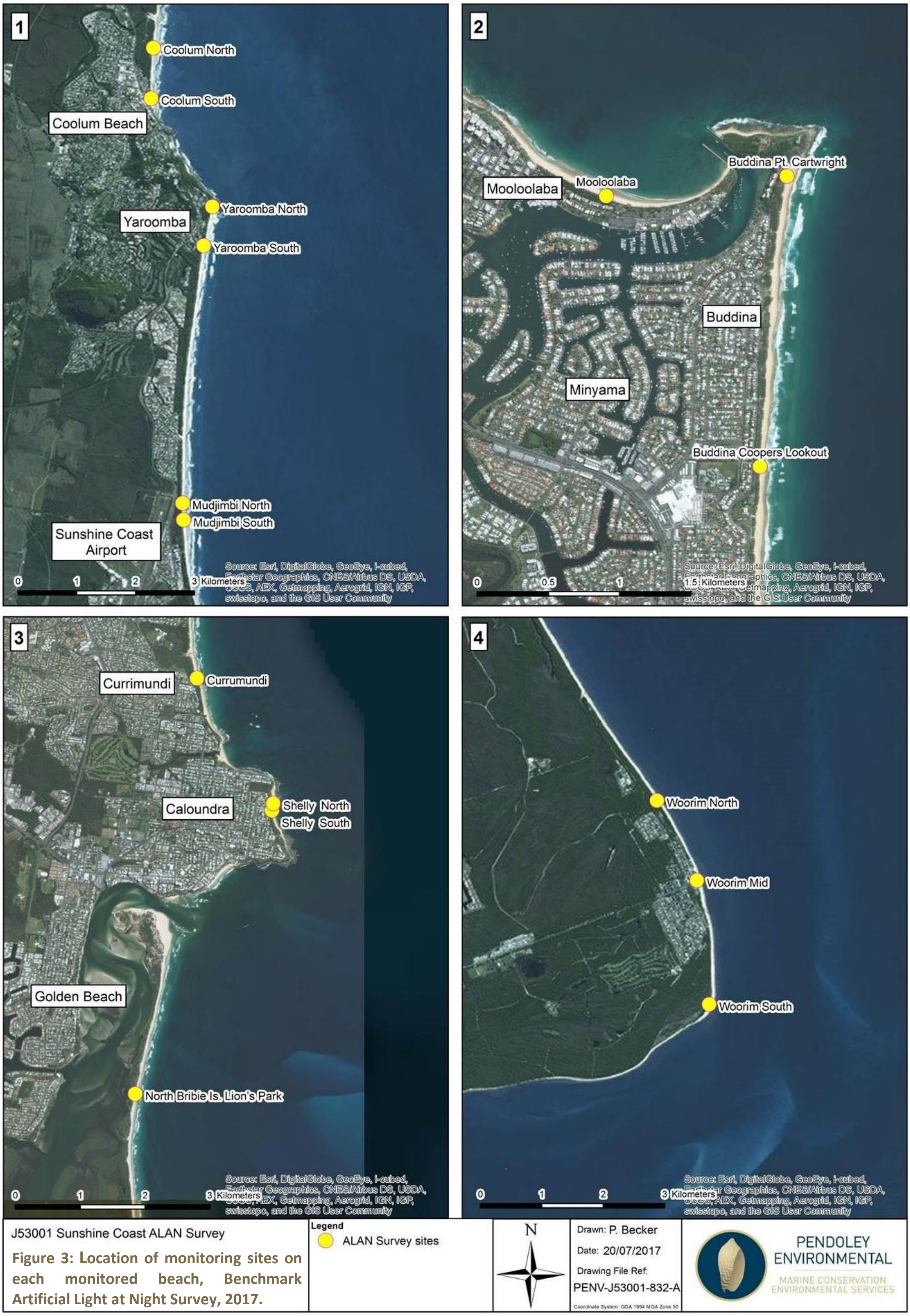



**Figure 3: Location of monitoring sites on each monitored beach, Benchmark Artificial Light at Night Survey, 2017.**

The current surveys were scheduled therefore, during the new moon phase of the lunar period (new moon: 24th June). Images captured on nights leading up to, and after the night of the new moon were scheduled to occur when the moon was not in the sky using predicted moon rise and moon set times to ensure moonlight did not decrease the quality of captured images.

### 2.1.2 Licensing Requirements

In consultation with the relevant staff at the Queensland Government, Department of Environment and Heritage Protection (DEHP) Permit and License Management (PALM) and Sunshine Coast Council it was determined that no licenses were required to execute these works.

## 2.2 Camera Deployment Locations

The Sky42™ light monitoring tool was deployed at, or near to locations agreed between Sunshine Coast Council, Moreton Bay Regional Council and PENV staff prior to initiation of surveys (**Figures 2** and **3; Table 2**). Multiple factors were considered in determining beaches for assessment: the position of Sky42™ at each monitored beach and included: the distribution of marine turtle nesting activity, duration of monitoring at the nesting beach, location of existing sources of light emissions, location of future, potential sources of light e.g. proposed developments, and proposed modifications to existing features that shield light e.g. changes to vegetation or dune profile. Duplicates of sites (on the same beach) were selected to capture the variance to landscape features within a beach suburb. The final camera locations are listed in **Table 2**.

**Table 2: Positon (decimal degrees) of Sky42™ monitoring tool at each monitoring site.**

| Monitoring Location | | | Sky42™ Position (decimal degrees) | |
|---|---|---|---|---|
| | Beach | Site | Latitude | Longitude |
| South Bribie | Woorim | South | -27.08717 | 153.20682 |
| | Woorim | Mid | -27.06892 | 153.20502 |
| | Woorim | North | -27.05714 | 153.19916 |
| Sunshine Coast | N Bribie Is. | Lion's Park | -26.83514 | 153.12926 |
| | Shelly | South | -26.79553 | 153.14821 |
| | Shelly | North | -26.79456 | 153.14838 |
| | Currimundi | Currimundi | -26.77707 | 153.13782 |
| | Buddina | Coopers /SLSC | -26.70069 | 153.13589 |
| | Buddina | Pt. Cartwright | -26.68220 | 153.13759 |
| | Mooloolaba | Mooloolaba | -26.68348 | 153.12619 |
| | Mudjimba | South | -26.59557 | 153.09770 |
| | Mudjimba | North | -26.59299 | 153.09756 |
| | Yaroomba | South | -26.55336 | 153.10078 |
| | Yaroomba | North | -26.54736 | 153.10211 |
| | Coolum | South | -26.53069 | 153.09279 |
| | Coolum | North | -26.52291 | 153.09311 |

Up to five images were taken at each site on each monitoring night. Additional data recorded included:

- Sky condition (cloudy vs clear);
- Estimated distance (m) to visible point source light;
- Bearing (°) of visible point source light;
- Bearing range (°) visible sky glow;
- Description of source (if known) e.g. town, vessel, channel marker, street lights; and
- Other relevant descriptive information e.g. light colour.

## 2.3 Light Measurements

Human eyesight has the ability to interpret both short and long-wavelength light, with peak sensitivity to mid-range wavelength visible light (Crawford 1949). In contrast, marine turtle eyesight, particularly in hatchlings, is adapted to marine environments and is relatively less responsive to long-wavelength light, with peak sensitivity in the short-wavelength (blue) region of the visible spectrum (Pendoley 2005).

The standard tool used for measuring light in a field setting is a light/lux meter, designed to measure light as perceived by humans, and it is therefore an inappropriate tool for quantifying light as perceived by organisms in their natural environment. This led to the in-house development of the Sky42™ camera (**Figure 4**), which is able to capture whole-of-sky, biologically meaningful light emissions, including sky glow quantified in magnitudes/arcsec$^2$, a unit of measurement that is emerging as a global standard (Zotti 2007; Rabaza et al. 2010; Kollath 2010; Kyba et al. 2010; Kyba et al. 2011; Falchi 2011; Aube 2016; Jerchow et al. 2017; Falchi et al. 2016; Bara 2017).

On each figure, for each monitoring site, data have been graphed to show average magnitude across the 360° horizon. The units (magnitude/arcsec$^2$) are astronomical units of luminance and a measure of the brightness of an extended area of sky. By convention the results are reported on an inverse scale with smaller values (15 – 17) representing very high sky glow while higher values (21 -22) are typical of a dark sky with little sky glow. Because larger magnitude values represent lower intensity light and smaller values represent higher intensity light, the scale on the graphs has been reversed for ease of reading and interpretation, i.e. an upward change in a graph represents an increase in light intensity.

The instrument internally houses a Canon PowerShot G12 camera with an unfiltered Raynox DCR-CF187PRO HD fish-eye lens within a protective case. The instrument also contains a temperature sensor, humidity sensor, infrared sensor, compass, bubble level, and a blue-filtered Sky Quality Meter (SQM).

The instrument is controlled by specialised circuitry and powered by a nickel-metal hydride (rechargeable) battery. Throughout the field survey, the cameras are prepared during the day and deployed at survey beaches in the late afternoon (**Figure 4**). At pre-programmed intervals from sunset until sunrise, the lid of the instrument opens, the camera takes a photo of the night sky at either three or 15 minute intervals as selected and then the lid closes again to reduce the risk of contamination or condensation on the lens.


**Figure 4: The Sky42™ system deployed just north of Lions Park, North Bribie Island.**

## 2.4 Zenith Light Measurements

SQM data are being used by researchers globally and the International Dark Sky Association uses this data to compare the quality of the night sky between international locations, so we present the data here for completeness.

The SQM results are not filtered for poor atmospheric conditions such as cloud, dust, haze, and wind. It is important to note that standard deviations do not represent a margin of error or an associated confidence interval, but represent the variation in observed light levels (Kyba et al. 2011, 2012).

## 2.5 Data Analysis

### 2.5.1 Raw Images and Isophote Maps

The fish-eye lens captures all visible light sources in a single circular image (**Figure 5a**) which encompasses the full 360° horizon and the overhead night sky. Image quality may be influenced by the moon, twilight, clouds, rain or humidity. Where a large enough data set permits, images are excluded from data analysis based on the presence of these features, or analysed separately for comparative purposes. If there are no perfectly clear, cloud free, images available from the survey period, the clearest images available are selected.

Images selected for analysis and presented within this report are, therefore the highest quality images from each site. In these surveys, the moon was not visible on any night, and the camera was deployed after dark to avoid twilight images. Images selected for analysis were the clearest images that were free of cloud (clear images). For analysis of cloudy sky conditions, we selected those with the most cloud, for comparative purposes.

Each image is processed using specialised software, “Sky Quality Camera” developed by Euromix Pty Ltd (Ljubljana, Slovenia). The software is licensed to, and calibrated against, each Sky42™ camera individually using a master camera calibrated in Slovenia by Euromix.

Two important characteristics of light emissions are intensity and colour, or ‘spectral output’. Raw images are used for qualitative interpretation of light types based on colour. White sky glow is indicative of white based lights (e.g. metal halide, halogen, fluorescent) while orange glow is produced by sodium vapour lights or flares.

An isophote map shows scaled levels of short wavelength light intensity in the night sky in units of magnitude (**Figure 5b**). The best quality images (i.e. those with the least influence from cloud, rain, wind, condensation, dust or moonlight) collected for each survey site and date are converted into an isophote (light level) contour map, analogous to a topographical contour map that connects points of equal elevation. The isophote maps are then used to quantify light emissions and track both spatial and temporal changes in night time sky illumination.

### 2.5.2 Measurement Units

Units of magnitudes per arc $sec^2$ (magnitude) quantify light intensity on an inverted logarithmic scale, i.e. higher values represent lower intensity light, while lower values represent higher intensity light (**Table 3**). For example, dark sky under natural conditions and in the absence of moonlight is magnitude 22, whilst brighter sky over urban areas is magnitude 17. The general range (in magnitude units) for typical night sky illumination are given in **Table 3.**

It is important to note that the colour coding used in isophote maps represents the scale of intensity of light across the entire spectrum and is not representative of the colour of light as perceived by the human eye, turtle eye or Sky42™ camera. For example, the large areas of green represent a dark night sky which appears to the human eye as dark blue to black. The orange areas represent the illuminated areas. The results represent light visible across the entire spectrum and is not weighted to the sensitivity of the human eye.

Turtles are most sensitive to short-wavelength light in the 350 – 490 nm range, however they are able to detect and respond to light across the entire visible spectrum from 400 nm – 700 nm. This visual acuity means that commercial light monitoring instruments are inappropriate for marine turtle light monitoring since they are weighted to the human eye and have a peak sensitivity at 550 nm and little or no sensitively at 400 nm or 700 nm. In contrast the Sky42™ system has the ability to quantify light across the entire visible spectrum, including the shortest and longest wavelengths. The images have therefore been processed to account for light from across the whole visible spectrum to include artificial lights rich in both blue and red wavelengths.

**Table 3: Qualitative interpretation of magnitude band values (Source: Unihedron Sky Quality Meter).** Use as guide only. Values below magnitude 17 represent light level greater than that described as 'very high' representative of an urban night sky horizon.

| Magnitude | Qualitative Interpretation | Qualitative Example of Interpretation |
|---|---|---|
| 21 – 22 | Very low | Ideal natural dark night sky horizon |
| 20 – 21 | Low | Typical rural night sky horizon |
| 19 – 20 | Moderate | Typical suburban night sky horizon |
| 18 – 19 | High | Typical urban night sky horizon |
| 17 – 18 | Very High | Poor urban night sky horizon |

## 2.6 Data Analysis

Each raw image (**Figure 5a**) was processed to produce a 360° isophote map of sky brightness in magnitudes/arcsec$^2$ (**Figure 5b**) together with an equirectangular panorama of the 360° view of both images that facilitated a more readily interpretable view of the night sky light-level (**Figures 5c** and **5d**).

Light intensity magnitude values were extracted for each pixel on the isophote map along each 1° bearing (0° – 359°) from the centre of the isophote to the edge of the image and the average calculated and plotted on a line graph as the y-axis with bearing (0° – 359°) on the x-axis (**Figure 5c**).

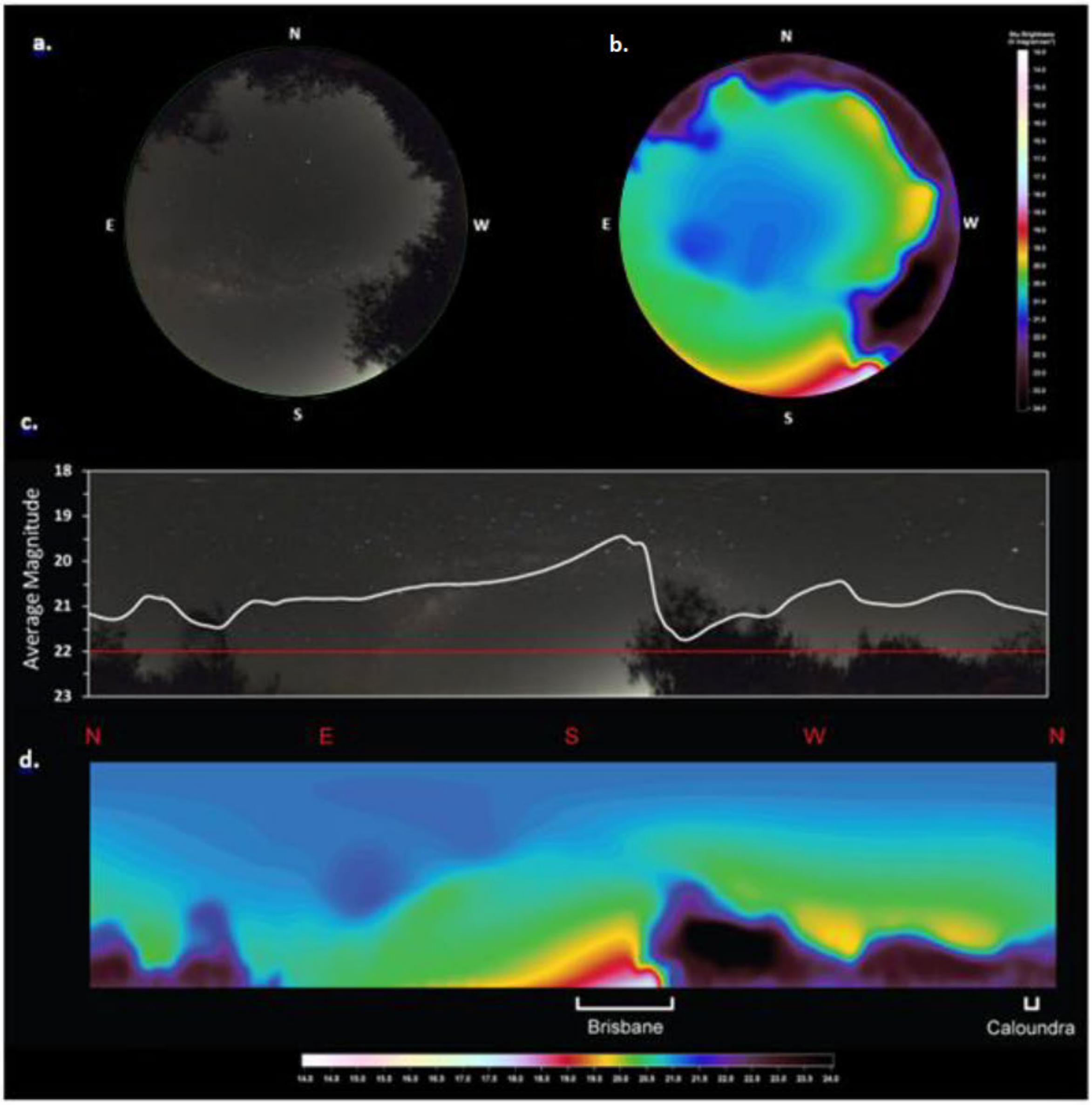



**Figure 5: Sky42™ output showing; a. typical image of night-sky captured by Sky42$^{TM}$; b. example isophote map of light levels across the visible spectrum (see Table 3 for interpretation); c. bearing (°) and average magnitude of measured light; d. isophote image of night sky shown 0° - 359°** Notes: X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red line: target magnitude, representative of a rural dark sky i.e. unaltered night sky horizon.

The bearing graphs (c.) are overlaid on the raw image from which the light intensity graph was generated, with a rising trend representing an increasing light intensity. The image used in analysis for each site was selected from a subset of images chosen based on image suitability for processing, i.e. images with clear atmosphere (i.e. no cloud, dust or haze), in the absence of moonlight and other image anomalies.

In the current analyses we have included images that represent various atmospheric conditions (cloudy and clear sky conditions) to, where possible:

- quantify variation in night sky brightness between clear and cloudy sky conditions; and
- illustrate variability, both across the sky in a single survey night and among locations and survey nights in cloudy sky conditions.

For sites with less light pollution, natural light sources such as stars are relatively more prominent. This results in a bearing chart with many localised peaks. For sites with more light pollution, bearing charts appear smoother in fine scale detail.

### 2.6.1 Sky Brightness Values (Magnitudes/Arcsec$^2$)

The units of sky brightness are given in astronomical units of magnitudes/arcsec$^2$. Values given within this report describe sky brightness for three separate 'zones' of the night sky (**Figure 6**). *'Zenith'* is the average value of light from 0º – 30º (directly above) which is less influenced by light sources on the horizon and therefore subject to variation both among and within survey nights, 'w*hole of sky'* is the average value of the entire night sky from 0º – 90º, and '*horizon'* which is the brightness of a 10° band around the horizon including light emissions from all land or ocean based sources from 80° - 90° only (excludes light in the sky above 80º).

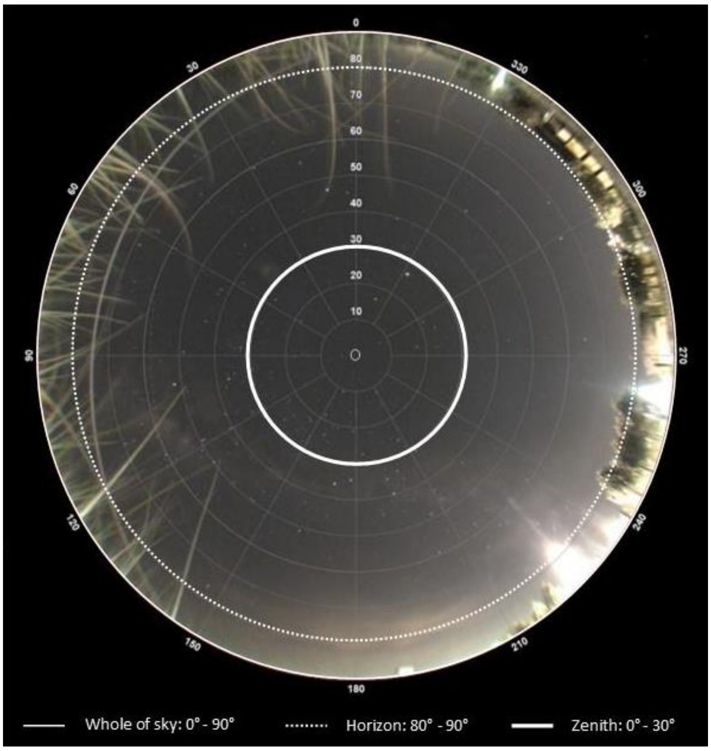



**Figure 6: Night sky sections for whole of sky, horizon and zenith.** Note: 0° is directly overhead.

## 2.7 Raw Images, Isophote Maps and Magnitude Values

In the remainder of this section, results for clear and cloudy sky conditions captured during monitoring surveys in June 2017 at each monitoring site are presented as follows:

a. **Figure**: showing an equirectangular panorama of the raw and isophote Sky42™ images of the night sky from each deployment site with average magnitude at each 1° bearing through 359° overlaid and with reference to identified primary (brightest) light sources; and

b. **Quantitative interpretation:** Descriptive interpretation of isophote maps which show relative levels of quantified light as magnitude bands within the visible spectrum; and

c. **Qualitative interpretation:** Description of the distribution, direction and relative intensity of night-time sky glow as it is perceived by the human eye shown in raw images captured by Sky42™.

The original 360° images from each of the monitoring sites are available in **Appendix B**. The likely sources of sky glow were identified using Google Earth and the 'lightpollutionmap' tool (www.lightpollutionmap). This tool uses satellite sourced VIIRS/DMSP/World Atlas overlays to provide an annual composite average light pollution image for globe. The map cannot be used for reliable quantitative analysis as the source data lacks both precision and accuracy and cannot be used for annual comparisons due to the large number of environmental factors involved in the generation of the maps. They are however extremely useful for the identification of regional sources of light emissions and for survey planning.

## 2.8 Lighting Audit

During the survey a 'Light Audit' was conducted with the goal of identifying single sources of visible point light, or potentially visible from the nesting beach. From a single position located near to the access point to each monitoring site or beach, a record was made of all visible point source light that included the bearing (°) and estimated distance (m) of the light from the observer's location, the estimated height (m) of the light source, the number of lights (*n*), the colour of the light and the type of structure it was affixed to. Any other relevant information was also recorded as comments.

In analysis, several of these lights are visible in the images and on the histogram showing average magnitude across the 360º horizon as steep peaks in magnitude value. These have been identified and labelled within.

## 2.9 Survey Limitations

### 2.9.1 Technical and Environmental Limitations

Changes to atmospheric and operational conditions are considerable, varying within and between nights. Data collected in this Benchmark ALAN survey provides a realistic sample, yet it is unlikely to capture the full range and variability of light conditions present over an entire year, or nesting season (~five months). This limitation is particularly important to consider if comparing light levels reported within to those potentially present at the nesting beach during the reproductive season.

The science of light quantification is complex. The development of a methodological approach to the quantification of biological meaningful light is in its infancy and there are limitations around what can be quantified and understood numerically. Findings within are considered in this context within the Discussion (**Section 4**) of this report.

Measurement of light emissions is influenced by distance and bearing between the monitoring site and the light source. The greater the distance between the light source and the monitoring site means the greater the overlap and merging of light emissions from multiple adjacent light sources. When sky glow from point sources merge in the overhead sky, it is not possible to isolate the light from a specific source. This is complication increases over distance, especially in moisture-laden marine atmospheres.

Clouds reflect and amplify light and where present, measured light intensity is a factor of cloud thickness, height and cover. Images with cloud cover present can only be compared to others with similar levels of cloud cover. Assessment of these factors is visual and is not quantified during processing.

Information regarding dune elevation profiles and topography at marine turtle nesting habitat was provided however in-depth spatial analysis was outside the scope of this study.

# 3 RESULTS

## 3.1 Bearing and Distance to Light Sources

In the current (2016/17) surveys, Sky42™ instruments were deployed at South Bribie Island (*n* = 3) and the Sunshine Coast (*n* = 13). The bearing (°) and distance (km) of all visible major light sources from each monitoring site have been identified using the 'lightpollutionmap' tool (**Figure 7**) and categorised as per **Tables 4** and **5.** The location of all monitoring sites relative to light pollution (as per the light pollution overlay) is given in **Appendix C.**

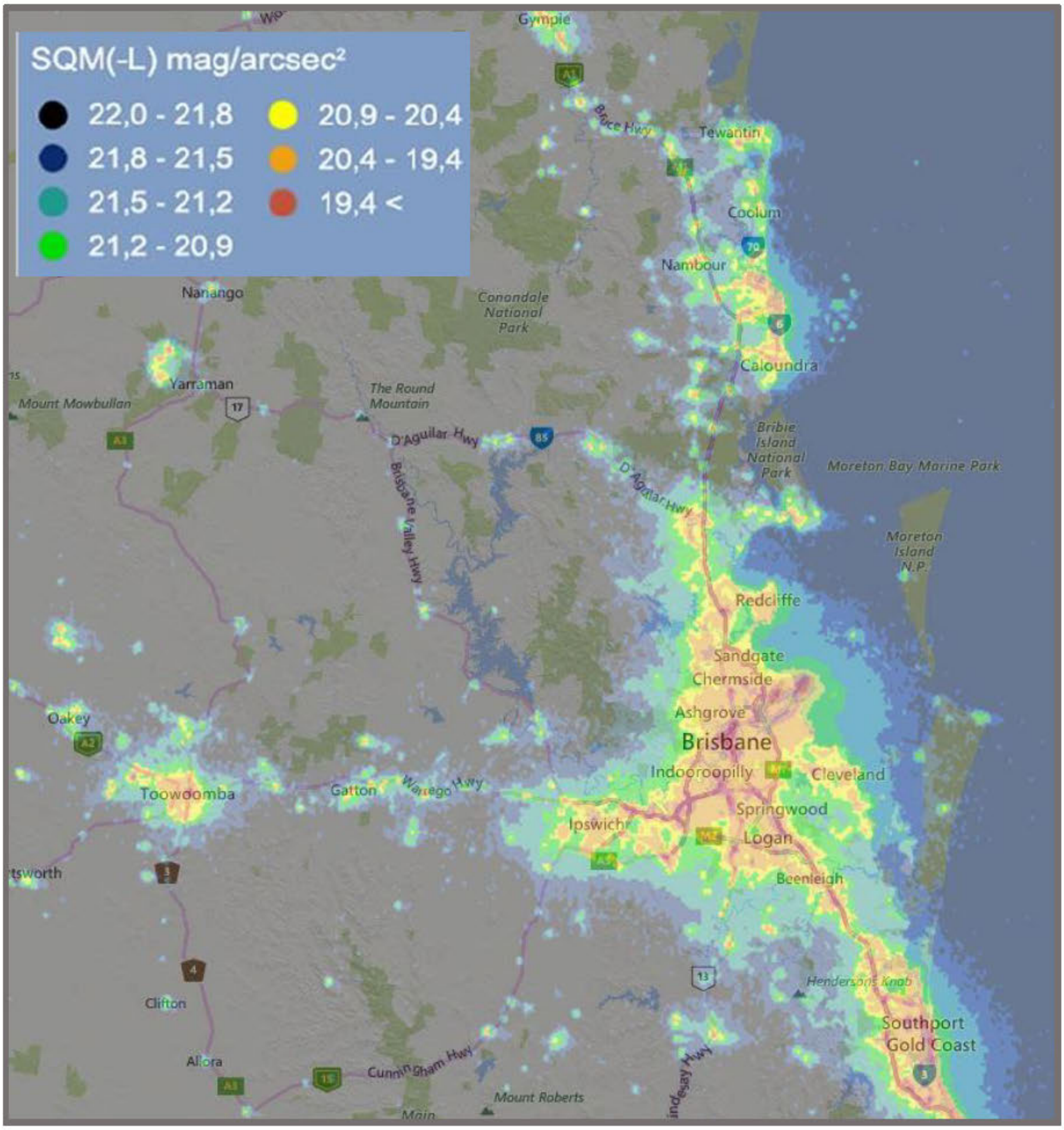



**Figure 7: Image of the Brisbane to Tewantin region generated using the 'lightpollutionmap' tool.** Approximate light intensity scale ranges from intense bright light (red, <19.4 mag/arcsec$^2$) to dark natural skies (dark grey, 22 mag/arcsec$^2$) (Source: Stare 2017).

**Table 4: Distance (km) to light sources noted within this report from each monitoring site (Table 3).** Coopers / SLSC: Coopers Lookout /Kawana SLSC; Moo'laba: Mooloolaba; Sun. Coast: Sunshine Coast; SC Airport: Sunshine Coast Airport

| | **Monitoring** | | **Light Source** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Beach** | **Location** | **Brisbane** | **Caloundra** | **Moo'laba** | **Sun. Coast** | **SC Airport** | **Mudjimba** | **Noosa Heads** |
| S. Bribie | Woorim | South | 46.0 | 33.0 | 45.0 | 48.6 | 54.5 | 53.5 | 76.8 |
| | Woorim | Mid | 47.6 | 31.0 | 43.8 | 45.8 | 52.6 | 51.6 | 74.9 |
| | Woorim | North | 49.0 | 29.5 | 42.1 | 45.0 | 51.4 | 50.2 | 73.3 |
| Sunshine Coast | N Bribie Is. | Lion's Park | 70.7 | 4.4 | 16.9 | 19.9 | 25.7 | 27.7 | 48.4 |
| | Shelly | South | 75.0 | 0.0 | 12.3 | 15.9 | 21.9 | 20.7 | 44.0 |
| | Shelly | North | 75.8 | 0.0 | 12.8 | 15.8 | 21.7 | 20.5 | 43.2 |
| | Currimundi | Currimundi | 77.8 | 2.2 | 10.5 | 13.7 | 19.6 | 18.4 | 41.9 |
| | Buddina | Coopers / SLSC | 85.0 | 10.0 | 3.0 | 6.0 | 11.5 | 10.3 | 29.3 |
| | Buddina | Pt. Cartwright | 87.0 | 12.0 | 2.0 | 4.5 | 9.8 | 8.6 | 31.4 |
| | Mooloolaba | Mooloolaba | 87.7 | 12.7 | 0.0 | 3.6 | 9.4 | 8.2 | 31.3 |
| | Mudjimba | South | 94.7 | 22.8 | 10.1 | 6.9 | 0.5 | 2.1 | 21.4 |
| | Mudjimba | North | 97.5 | 23.3 | 10.3 | 6.8 | 0.4 | 2.3 | 21.2 |
| | Yaroomba | South | 100.0 | 27.4 | 14.5 | 11.4 | 5.9 | 6.6 | 17.4 |
| | Yaroomba | North | 101.0 | 27.9 | 15.3 | 12.2 | 6.6 | 7.5 | 16.5 |
| | Coolum | South | 104.0 | 30.0 | 17.3 | 14.0 | 8.3 | 9.3 | 14.7 |
| | Coolum | North | 105.0 | 31.0 | 18.1 | 14.9 | 9.0 | 10.3 | 13.8 |

**Table 5: Bearing (°) to light sources noted within this report from each monitoring site (Table 3).** Coopers / SLSC: Coopers Lookout /Kawana SLSC; Moo'laba: Mooloolaba; Sun. Coast: Sunshine Coast; SC Airport: Sunshine Coast Airport

| | **Monitoring** | | **Light Source** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Beach** | **Location** | **Brisbane** | **Caloundra** | **Moo'laba** | **Sun. Coast** | **SC Airport** | **Mudjimba** | **Noosa Heads** |
| S. Bribie | Woorim | South | 180 - 212 | 345 - 351 | 350 | 348 | 347 | 348 | 352 |
| | Woorim | Mid | 182 - 211 | 346 - 352 | 349 | 348 | 347 | 348 | 352 |
| | Woorim | North | 181 - 209 | 347 - 352 | 350 | 348 | 348 | 348 | 352 |
| Sunshine Coast | N Bribie Is. | Lion's Park | 175 - 194 | 351 - 030 | 358 | 352 | 350 | 352 | 355 |
| | Shelly | South | 176 - 193 | 158 - 005 | 351 | 344 | 344 | 346 | 354 |
| | Shelly | North | 177 - 195 | 158 - 005 | 350 | 343 | 344 | 345 | 354 |
| | Currimundi | Currimundi | 176 - 194 | 155 - 204 | 353 | 346 | 345 | 347 | 354 |
| | Buddina | Coopers/SLSC | 175 - 190 | 169 - 192 | 325 | 325 | 335 | 336 | 352 |
| | Buddina | Pt. Cartwright | 177 - 190 | 171 - 191 | 280 | 311 | 330 | 332 | 350-355 |
| | Mooloolaba | Mooloolaba | 175-192 | 180-169 | 250 - 308 | 323 | 336 | 341 | 350-358 |
| | Mudjimba | South | 174 – 189 | 167 - 172 | 164 | 175 | 220 | 183 | 347-04 |
| | Mudjimba | North | 174 - 189 | 167 - 172 | 164 | 175 | 213 | 181 | 347-04 |
| | Yaroomba | South | 184 | 165-210 | 170 | 165-210 | 193 | 184 | 348-05 |
| | Yaroomba | North | 184 | 170-220 | 171 | 170-220 | 192 | 184 | 348-05 |
| | Coolum | South | 184 | 171 | 168 | 175 | 184 | 178 | 349-08 |
| | Coolum | North | 184 | 172 | 170 | 176 | 183 | 178 | 348-09 |

## 3.2 Average Magnitude in 2017

**Table 6** details average magnitude for 'whole of sky' (0° - 90°) 'zenith' (0° - 30°) and 'horizon' (80° - 90°) from each monitoring site (see **Figure 6, Section 2.6.1** for description) during clear sky and cloudy sky conditions where available. **Figure 8** provides graphic summary of horizon and zenith brightness at each monitored site.

**Table 6: Average magnitude for 'whole of sky' and 'horizon' at each monitoring site in both clear and cloudy conditions (where available) in June 2017.** Refer to Figures 1 and 2 for maps of monitoring sites. Grey cells: cloudy sky images were not collected at these sites in this study. Coopers / SLSC: Coopers Lookout /Kawana SLSC.

| | Monitoring | | Clear Sky | | | Cloudy Sky | | |
|---|---|---|---|---|---|---|---|---|
| | Beach | Location | Whole | Horizon | Zenith | Whole | Horizon | Zenith |
| S. Bribie Is. | Woorim | South | 20.91 | 20.49 | 21.04 | | | |
| S. Bribie Is. | Woorim | Mid | 20.27 | 18.20 | 20.41 | | | |
| S. Bribie Is. | Woorim | North | 20.79 | 20.51 | 20.91 | | | |
| Sunshine Coast | Nth Bribie Is. | Lion's Park | 20.71 | 19.94 | 20.83 | | | |
| Sunshine Coast | Shelly | South | 20.45 | 19.29 | 20.67 | 20.23 | 19.26 | 20.48 |
| Sunshine Coast | Shelly | North | 20.47 | 19.56 | 20.62 | 19.60 | 20.02 | 19.80 |
| Sunshine Coast | Currimundi | Currimundi | 20.24 | 19.41 | 20.34 | 20.06 | 18.80 | 20.22 |
| Sunshine Coast | Buddina | Coopers / SLSC | 19.59 | 18.55 | 19.72 | 17.80 | 18.23 | 17.66 |
| Sunshine Coast | Buddina | Coopers / SLSC a. | 19.80 | 19.19 | 19.93 | | | |
| Sunshine Coast | Buddina | Coopers / SLSC b. | 19.73 | 19.23 | 19.92 | | | |
| Sunshine Coast | Buddina | Pt. Cartwright | 20.09 | 19.05 | 20.19 | | | |
| Sunshine Coast | Mooloolaba | Mooloolaba | 19.67 | 18.79 | 19.77 | 16.84 | 18.01 | 16.81 |
| Sunshine Coast | Mudjimba | South | 20.37 | 18.52 | 20.51 | | | |
| Sunshine Coast | Mudjimba | North | 20.51 | 19.24 | 20.64 | | | |
| Sunshine Coast | Yaroomba | South | 20.74 | 19.75 | 20.86 | | | |
| Sunshine Coast | Yaroomba | North | 20.76 | 20.02 | 20.85 | | | |
| Sunshine Coast | Coolum | South | 19.48 | 17.90 | 19.62 | | | |
| Sunshine Coast | Coolum | North | 20.19 | 19.14 | 20.31 | | | |

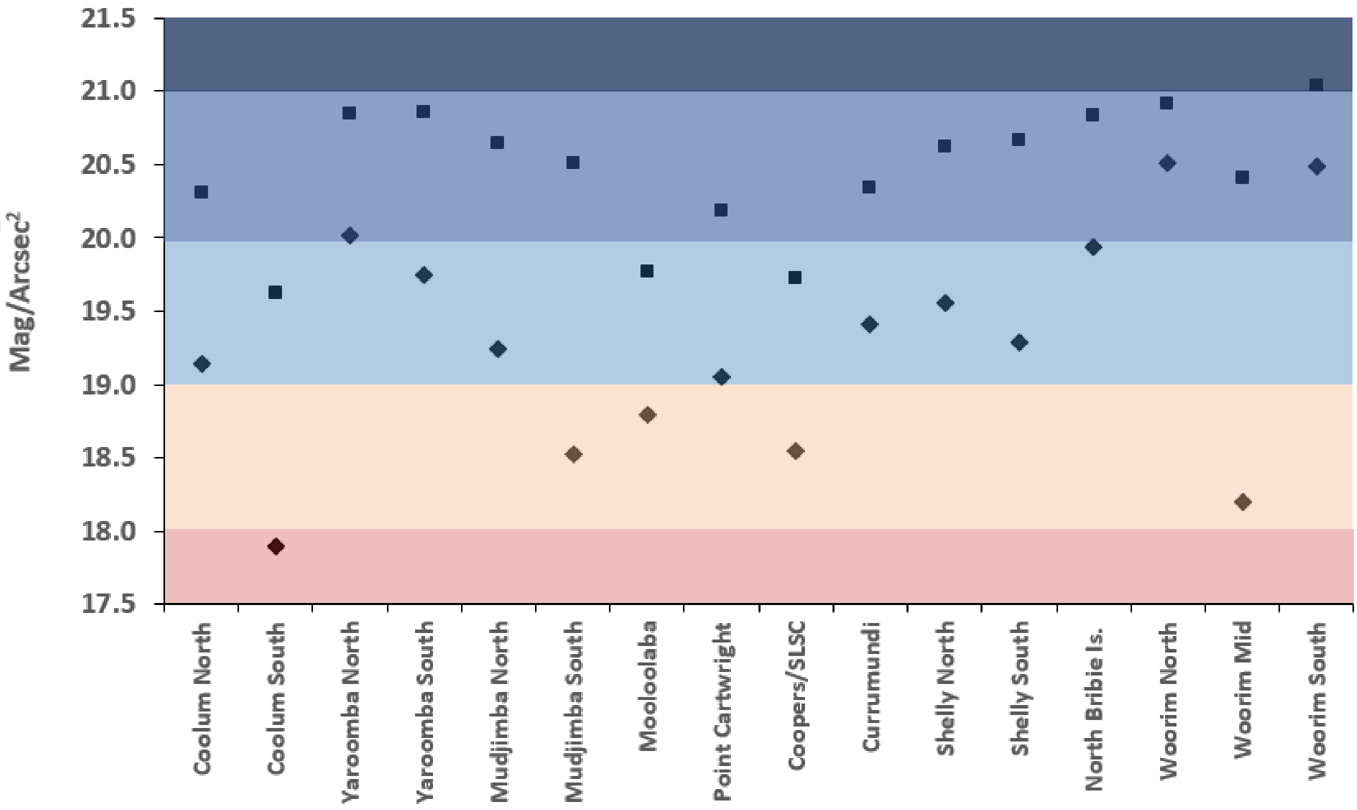



**Figure 8: Summary of horizon and zenith average magnitude values for each monitoring site in 2017 showing position of each value within the relevant magnitude band, colour coded as per Table 3**. Black diamonds: horizon brightness; black squares: zenith brightness.

### 3.2.1 South Bribie Island

#### 3.2.1.1 Woorim Beach South

Average 'whole of sky' magnitude from the monitoring site at Woorim Beach – south on a clear night was 20.91, zenith was 21.04 and the horizon was 20.49. **Figure 9** shows a peak in sky glow intensity (average magnitude) towards the south that originates from the Brisbane - Gold Coast region. Sky glow from Brisbane was blocked at its westerly extent by trees situated along the dune line. Cumulative glow from the Woorim urban area, together with the urban areas stretching from Caloundra/Golden Beach to Coolum, can be seen in the north-west above the tree line.

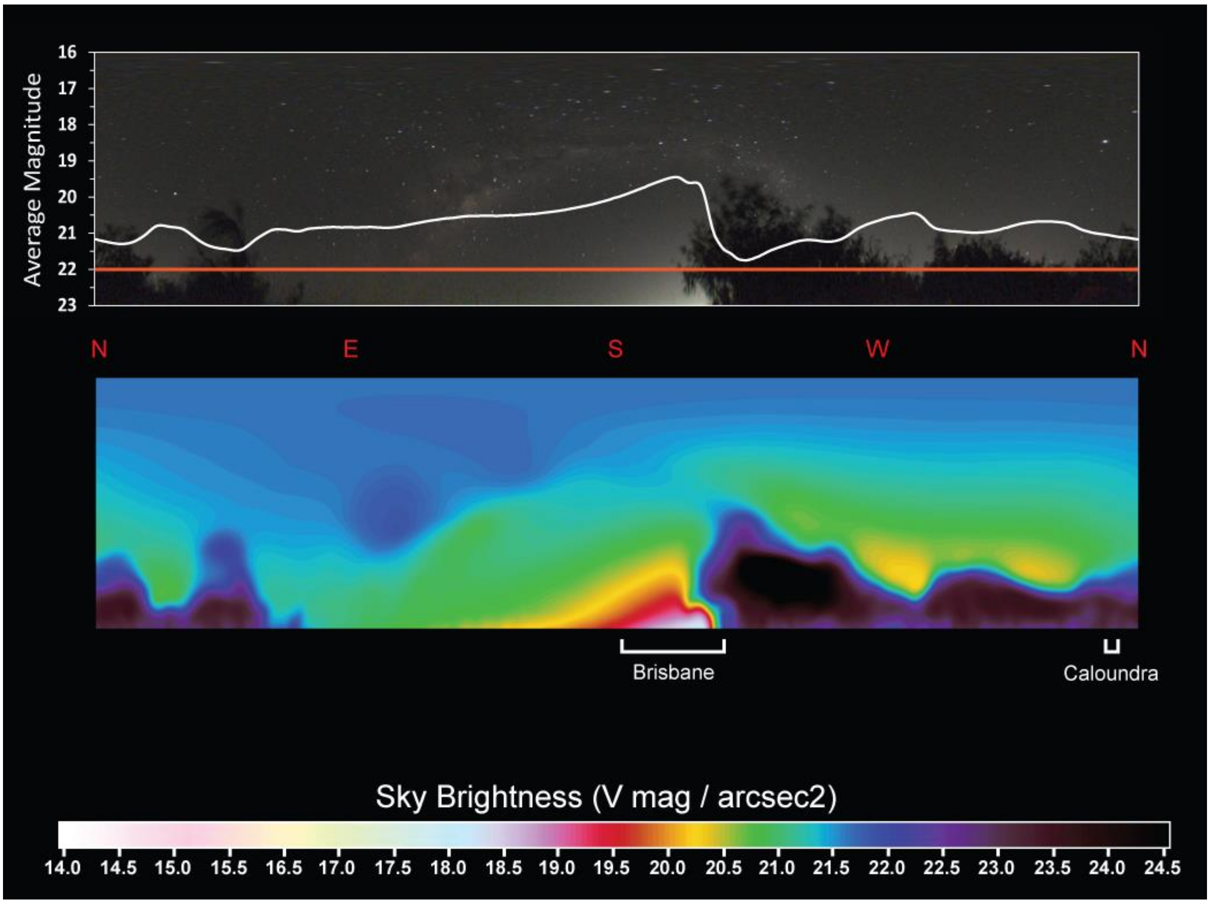



**Figure 9**: **Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Woorim beach (south), Bribie Island.** X axis: bearing from 0º - 359º Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.1.2 Woorim Beach Mid

Average 'whole of sky' magnitude from the monitoring site Woorim Beach – mid on a clear night was 20.27, zenith was 20.41 and the horizon was 18.20. **Figure 10** shows an increase in light intensity from the direction of Brisbane – Gold Coast (to the south), a peak over point source lights in the carpark immediately adjacent to the monitoring site (south west to west) and glow from the direction of Caloundra/Golden Beach to Coolum urban zones to the north. The long grass reflecting light in the east of the image is making a negligible contribution to the horizon and the whole of sky values.

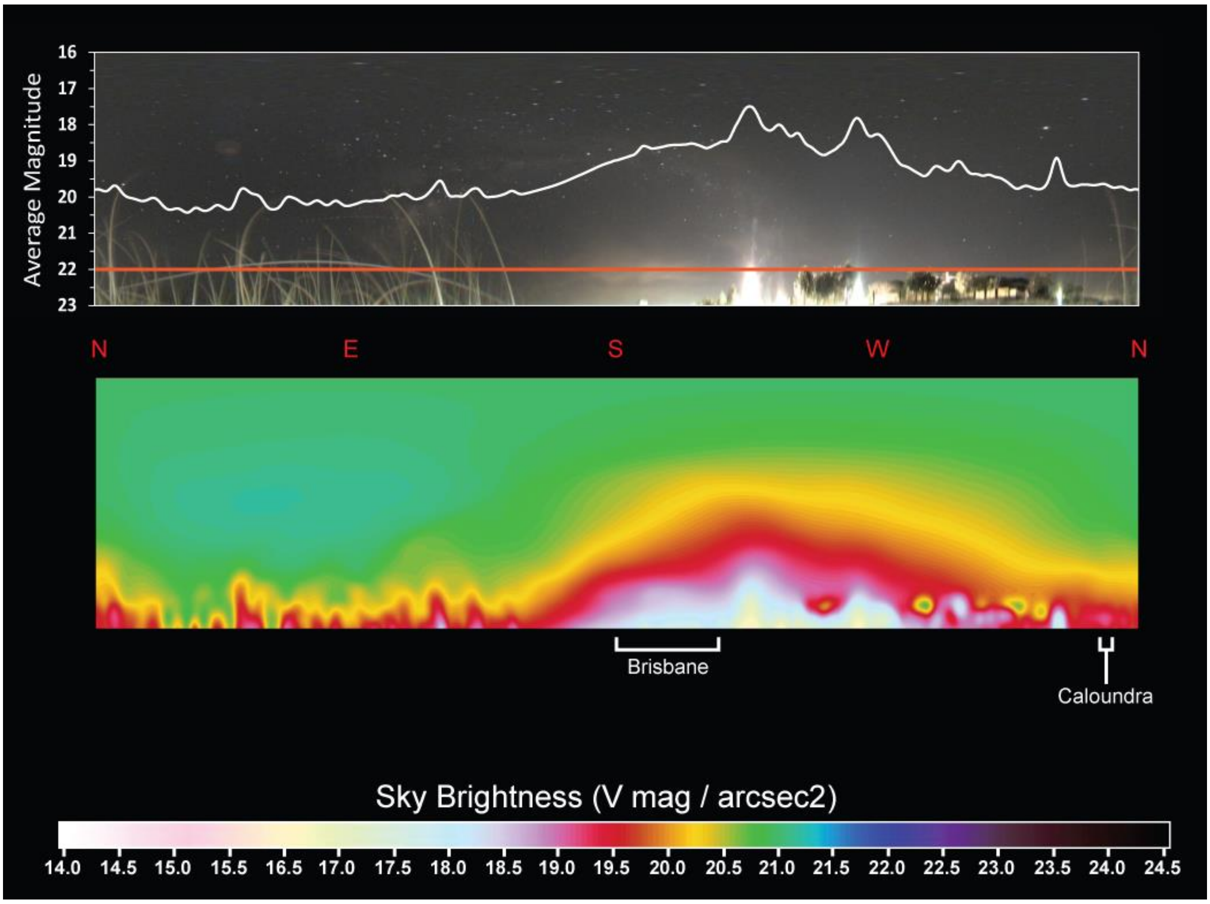



**Figure 10: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Woorim beach (mid), Bribie Island.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.1.3 Woorim Beach North

Average 'whole of sky' magnitude from the monitoring site Woorim Beach – north on a clear night was 20.79, zenith was 20.91 and the horizon was 20.51. **Figure 11** shows cumulative sky glow, shielded by dense vegetation from south to west and peaking in the north. The glow originated from the Caloundra to Coolum urban areas which include multiple commercial, industrial and residential sources of light emissions.

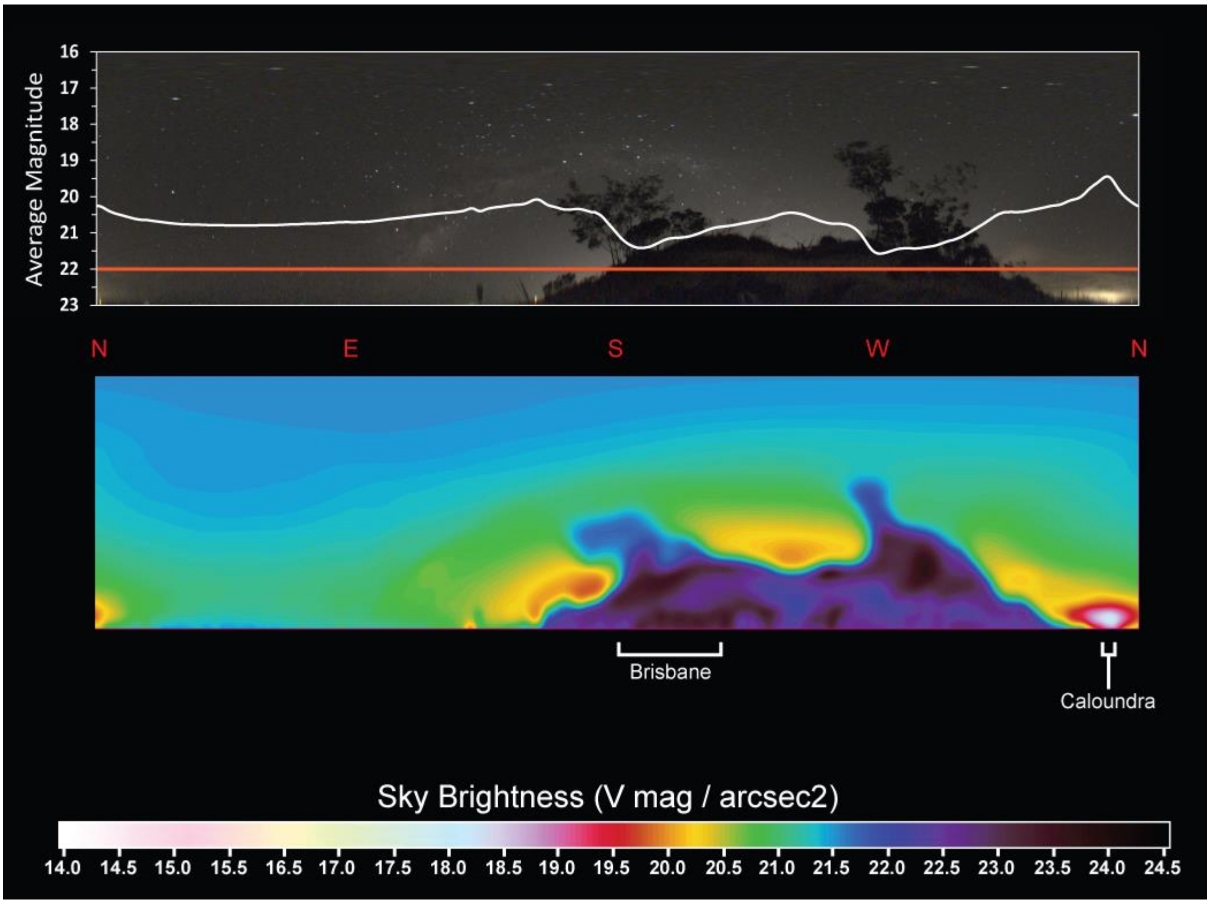



**Figure 11: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Woorim beach (north), Bribie Island.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.2 North Bribie Island

Average 'whole of sky' magnitude from the monitoring site on North Bribie Island on a clear night was 20.71, zenith was 20.83 and the horizon was 19.94. **Figure 12** shows three distinct zones of point sources and sky glow; the cumulative sky glow from and multiple point sources of urban lights located between Caloundra and Coolum to the north, orange glow from the Brisbane – Gold Coast areas > 50 km to the south and glow to the west from the direction of Pelican Waters and Golden Beach.

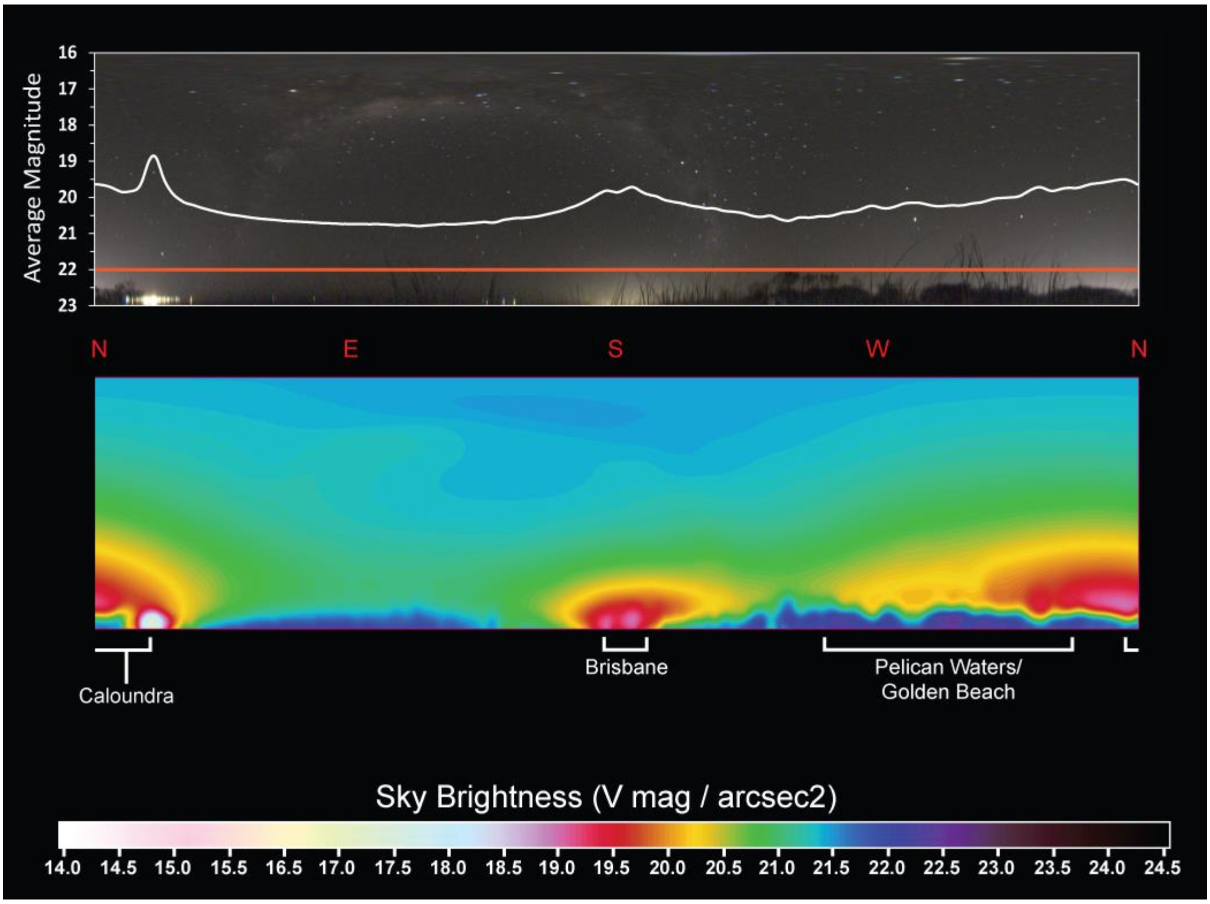



**Figure 12: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Lions Park, North Bribie Island.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.3 Shelly Beach

#### 3.2.3.1 Shelly Beach south - clear

Average 'whole of sky' magnitude from the monitoring site on Shelly Beach – south on a clear night was 20.45, zenith was 20.67 and the horizon was 19.29. **Figure 13** shows a consistently elevated area of sky glow from south to north across the entire western horizon originating from Brisbane – Gold Coast to the south, Caloundra located immediately adjacent to Shelly beach and the urban zones between Currimundi and Coolum to the north-north west.

Two point sources of note are visible in his image, in the north-west of **Figure 13** is a street light and [redacted]

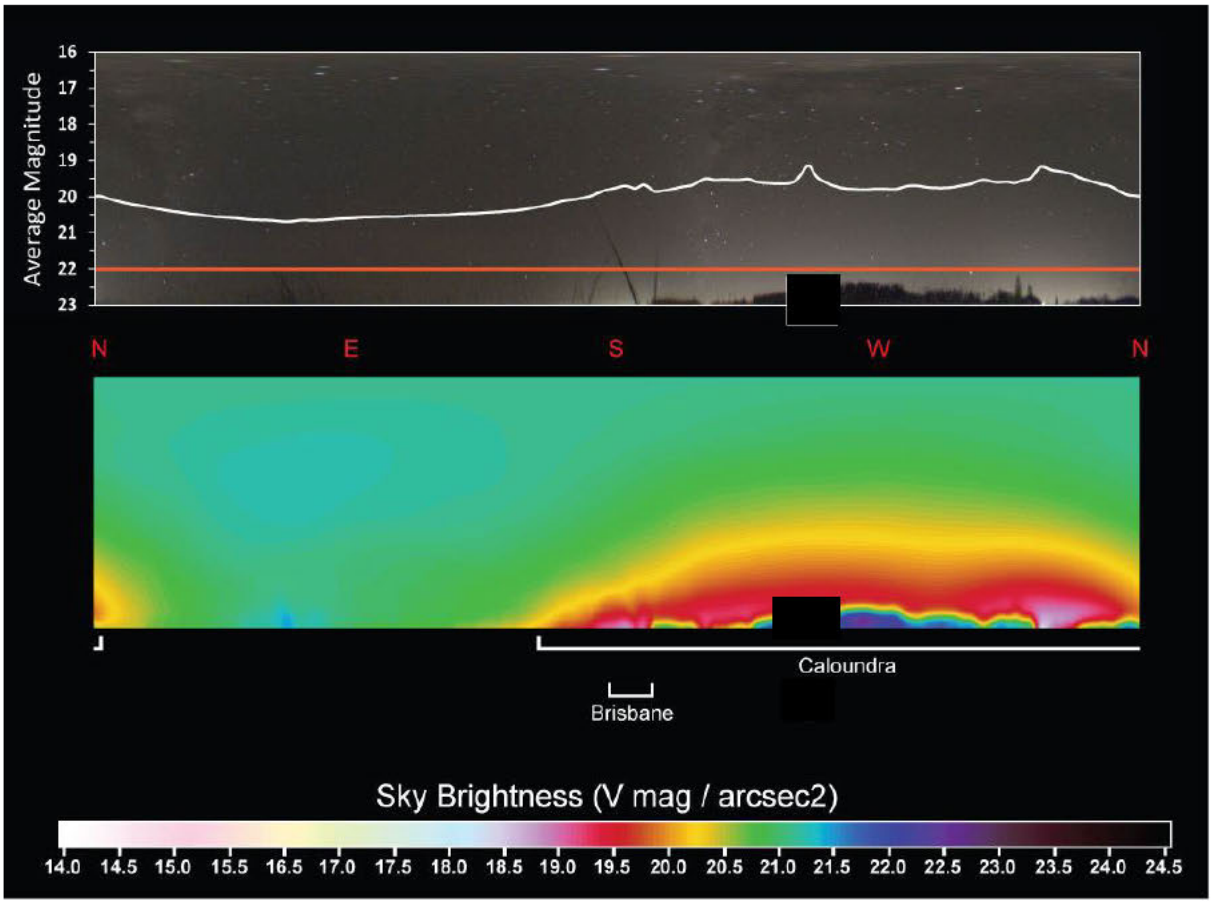



**Figure 13: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Shelly Beach – south, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.3.2 Shelly Beach south - cloudy

Average 'whole of sky' magnitude from the monitoring site on Shelly Beach – south on cloudy night was 20.23, zenith was 20.48 and the horizon was 19.26. Light sources in **Figure 14** are as per **Figure 13** [redacted] and appear brighter overall due to the scattering and reflective qualities of the (sparse) cloud in the image.

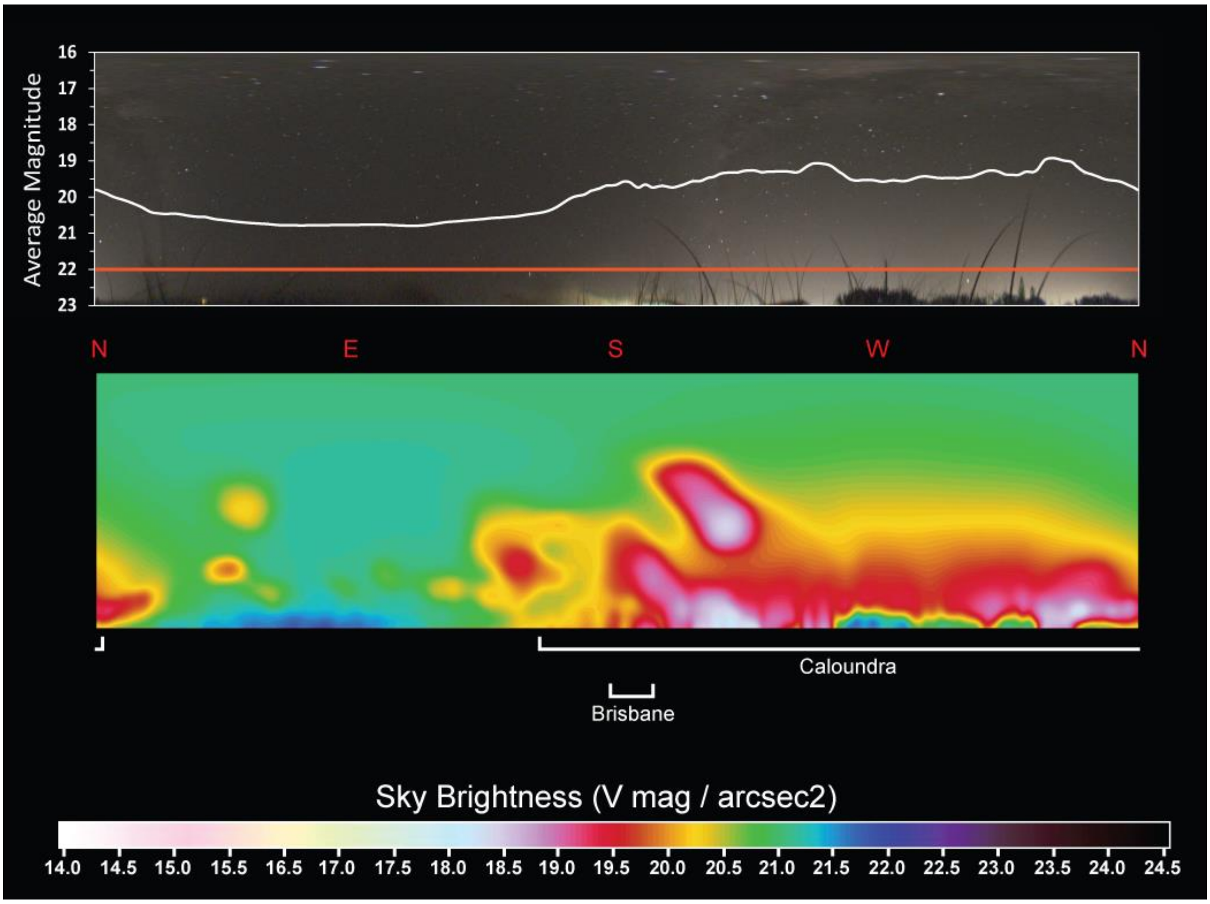



**Figure 14: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Shelly Beach – south, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.3.3 Shelly Beach north - clear

Average 'whole of sky' magnitude from the monitoring site on Shelly Beach – north on a clear night was 20.47, zenith was 20.62 and the horizon was 19.56. Visible light shown in the south of **Figure 15** represents several point sources of light located on the horizon at the very southern end of the beach originating from a public area/carpark, sky glow from Caloundra in the west merges with the glow from Woorim and the Brisbane/Gold Coasts area in the south. Glow from the Currimundi to Coolum urban areas extend around the northern horizon while a row of residential properties screened behind a thick line of vegetation in the western half of the image appeared to contribute a substantial amount of light to the local sky glow over this survey location.

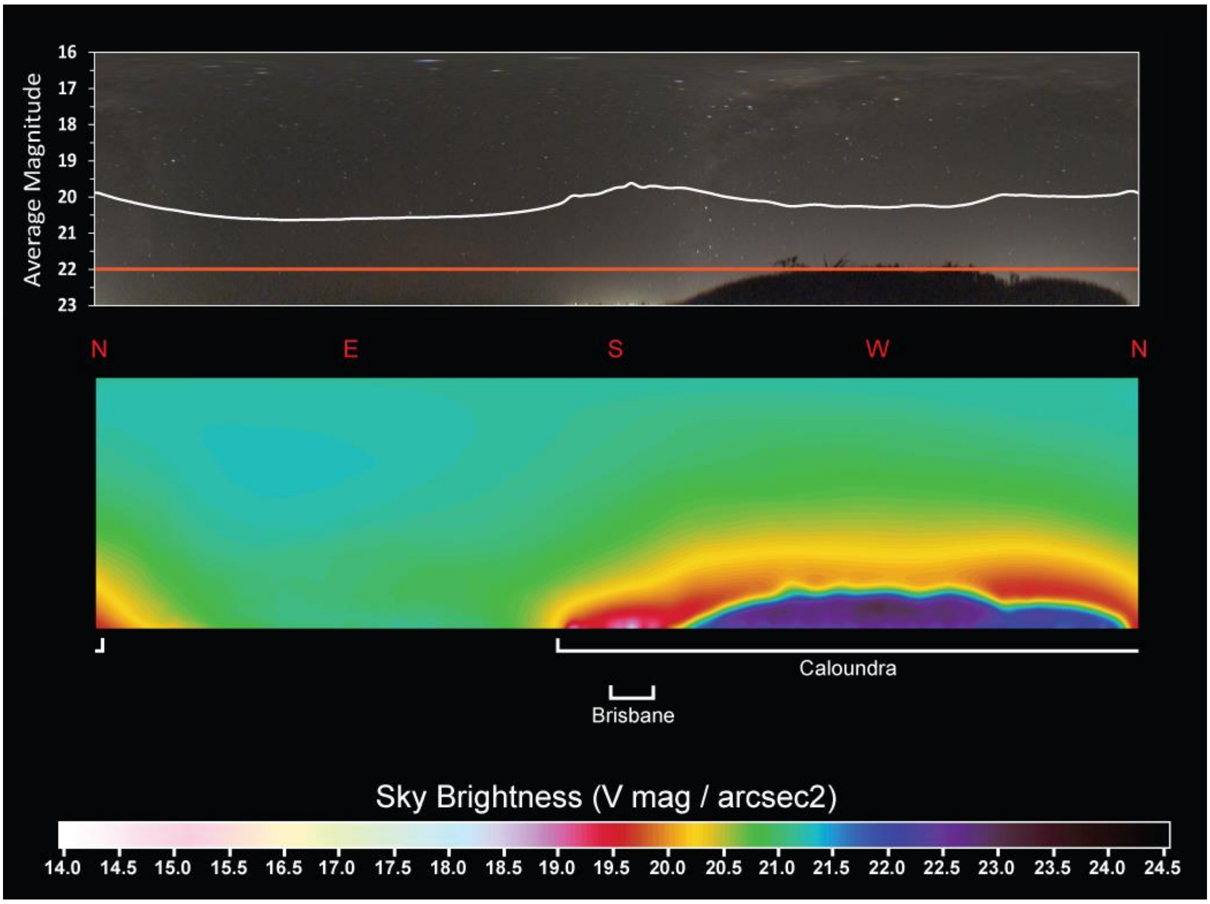



**Figure 15: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Shelly Beach – north, Sunshine Coast.** X axis: bearing from 0º - 359º, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.3.4 Shelly Beach north - cloudy

Average 'whole of sky' magnitude from the monitoring site on Shelly Beach – north on a cloudy night (with sparse cloud) was 19.60, zenith was 19.80 and the horizon was 20.02. The very bright area in the south of **Figure 16** shows reflected light from the direction of the public carpark and from the Brisbane/Gold Coast area further to the south. Overhead clouds substantially increases the area of sky illuminated and the intensity of the sky glow scattered and reflected from urban areas to the west at Caloundra and to the north from the Currimundi to Coolum.

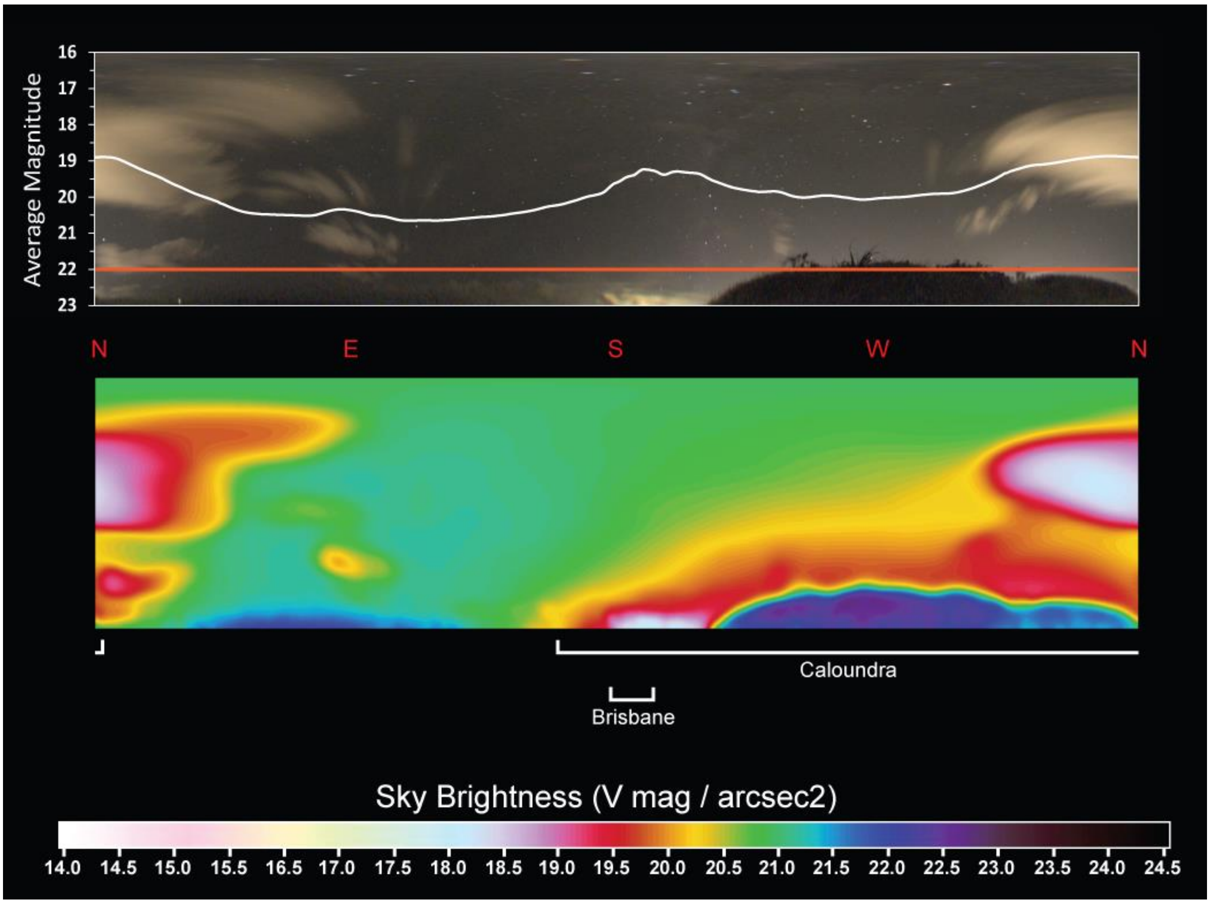



**Figure 16: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Shelly Beach – north, Sunshine Coast**. X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.4 Currimundi

#### 3.2.4.1 Currimundi - clear

Average 'whole of sky' magnitude from the monitoring site on Currimundi Beach on a clear night was 20.24, zenith was 20.34 and the horizon was 19.41. The primary light sources were cumulative glow from Caloundra/Golden Beach and Brisbane/Gold Coast in the south and the Buddina to Coolum region of the Sunshine Coast in the north (**Figure 17**). Vegetation located in the south-west of the image provided some shielding from glow on the horizon at this orientation. There were no nearby sources of light specific to this site that were detectable from the monitoring site.

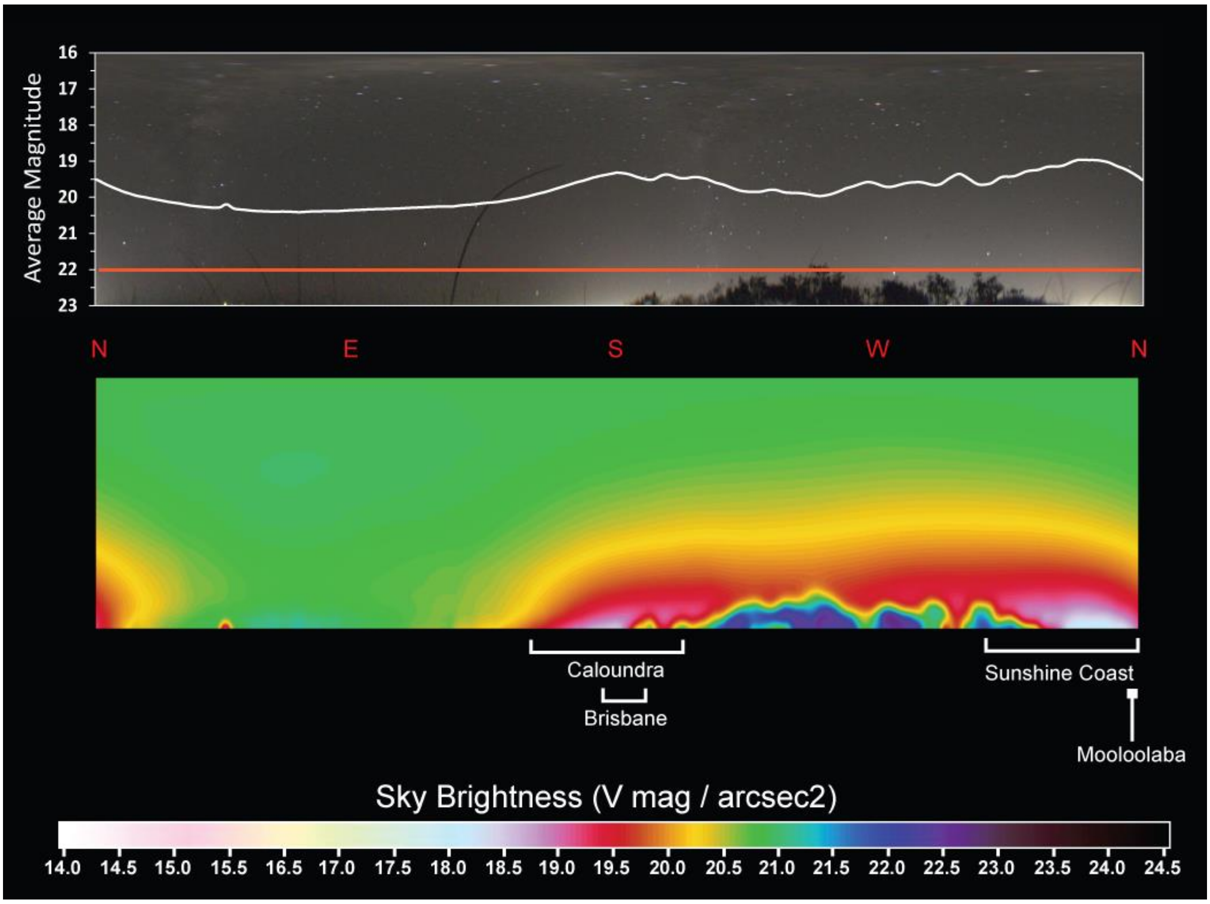



**Figure 17: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Currimundi Beach, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$).Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.4.2 Currimundi - cloudy

The 'whole of sky' magnitude from the monitoring site on Currimundi Beach on a cloudy night (with sparse cloud) was 20.06, zenith was 20.22 and the horizon was 18.80. The primary light sources were cumulative glow from Caloundra/Golden Beach and Brisbane/Gold Coast in the south and the Buddina to Coolum region of the Sunshine Coast and Sunshine Coast airport (and adjacent roadworks) in the north (**Figure 18**). The elevated and variable intensity of glow across the whole night sky is due to reflection of light off sparse patches of low cloud.

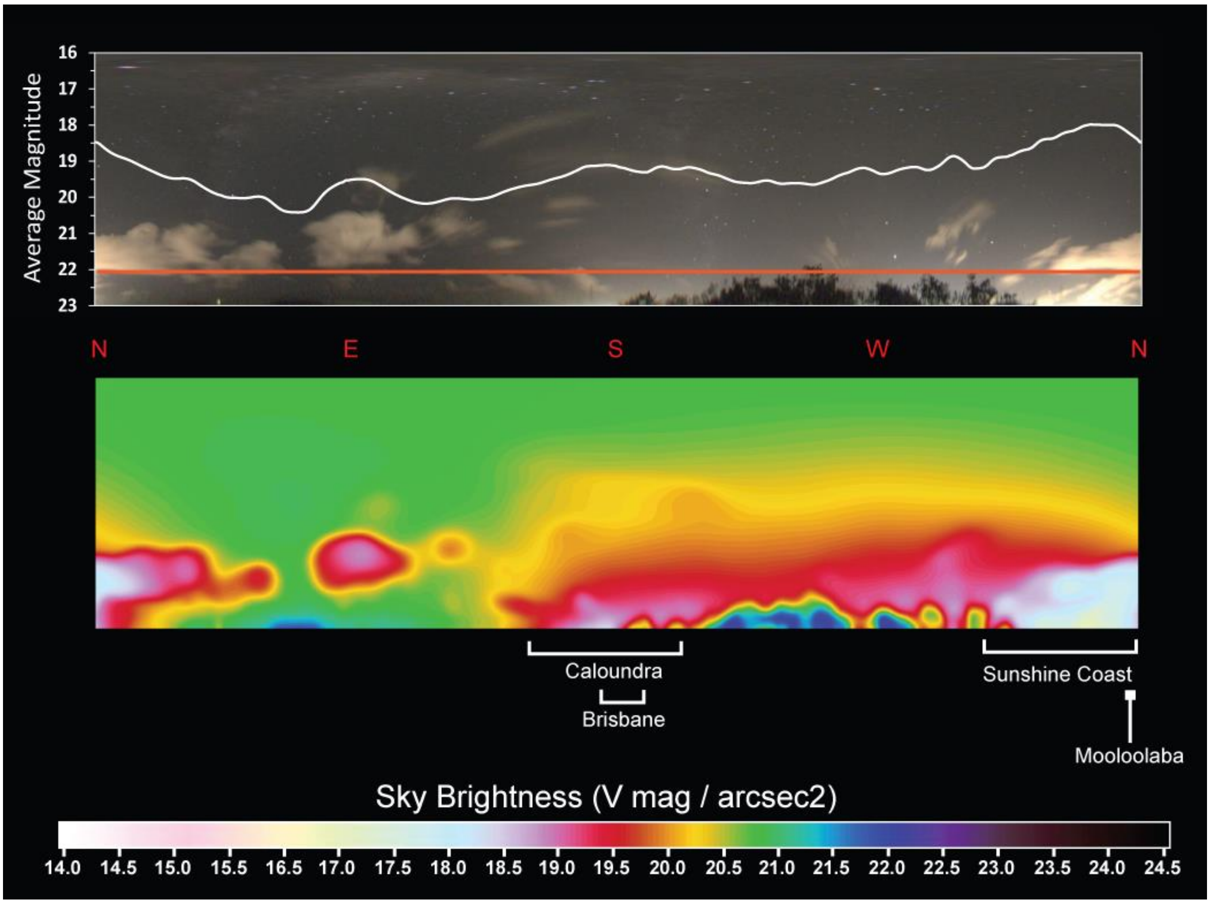



**Figure 18**: **Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Currimundi beach, Sunshine Coast**. X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.5 Buddina

#### 3.2.5.1 Cooper's Lookout/Kawana SLSC – clear

The 'whole of sky' magnitude from the monitoring site at Coopers Lookout/Kawana SLSC on a clear night was 19.55, zenith was 19.72 and the horizon was 18.55. Sky glow from the urban areas between this site and Caloundra, approximately 10 km to the south, is clearly visible on the southern horizon. Locally (200 – 300 m away), light from the Kawana Waters Surf Life Saving Club (SLSC) and its associated parking lot lights, are visible through and over the trees, which provide some shielding, in the south and west of the image (**Figure 19)**. The discrete peaks in the average magnitude values graph located on bearings between the south west and north-west arise from very bright individual point sources of light located in the carpark.

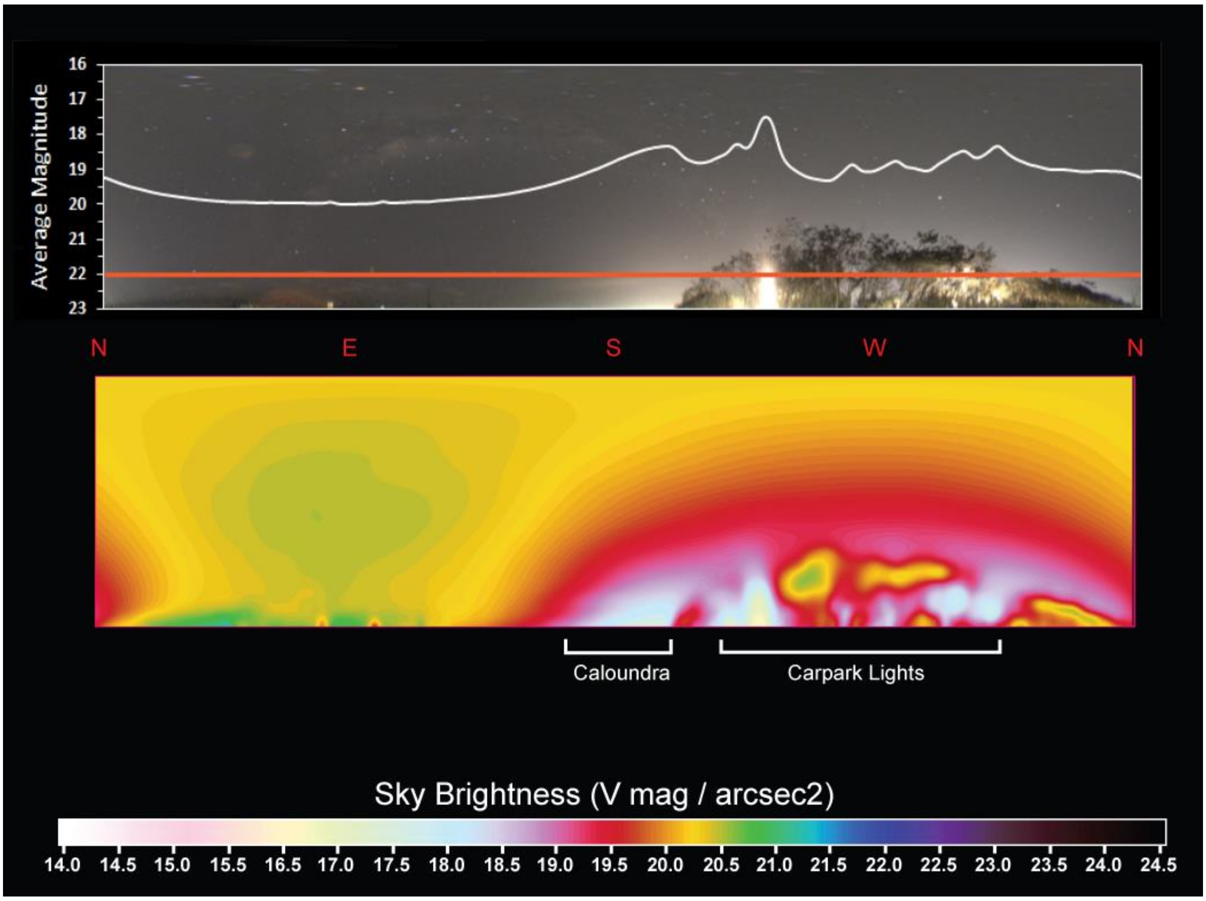



**Figure 19: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Coopers Lookout/Kawana SLSC beach, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.5.2 Cooper's Lookout/Kawana SLSC - cloudy

The 'whole of sky' magnitude from the monitoring site at Coopers Lookout/Kawana SLSC on a cloudy night was 17.80, zenith was 17.66 and the horizon was 18.23 and are shown together with clear sky values for zenith and horizon in **Figure 20**. Light from parking lot lights and from the Surf Life Saving Club are amplified by the low cloud cover, locally elevating sky brightness in the west of the image. Sky glow from the urban areas south towards Caloundra is also elevated by the cloud cover (**Figure 20**). Quantified variation in horizon and zenith brightness under cloudy compared to clear, skies at Coopers Lookout/Kawana SLSC is shown in **Figure 21**.

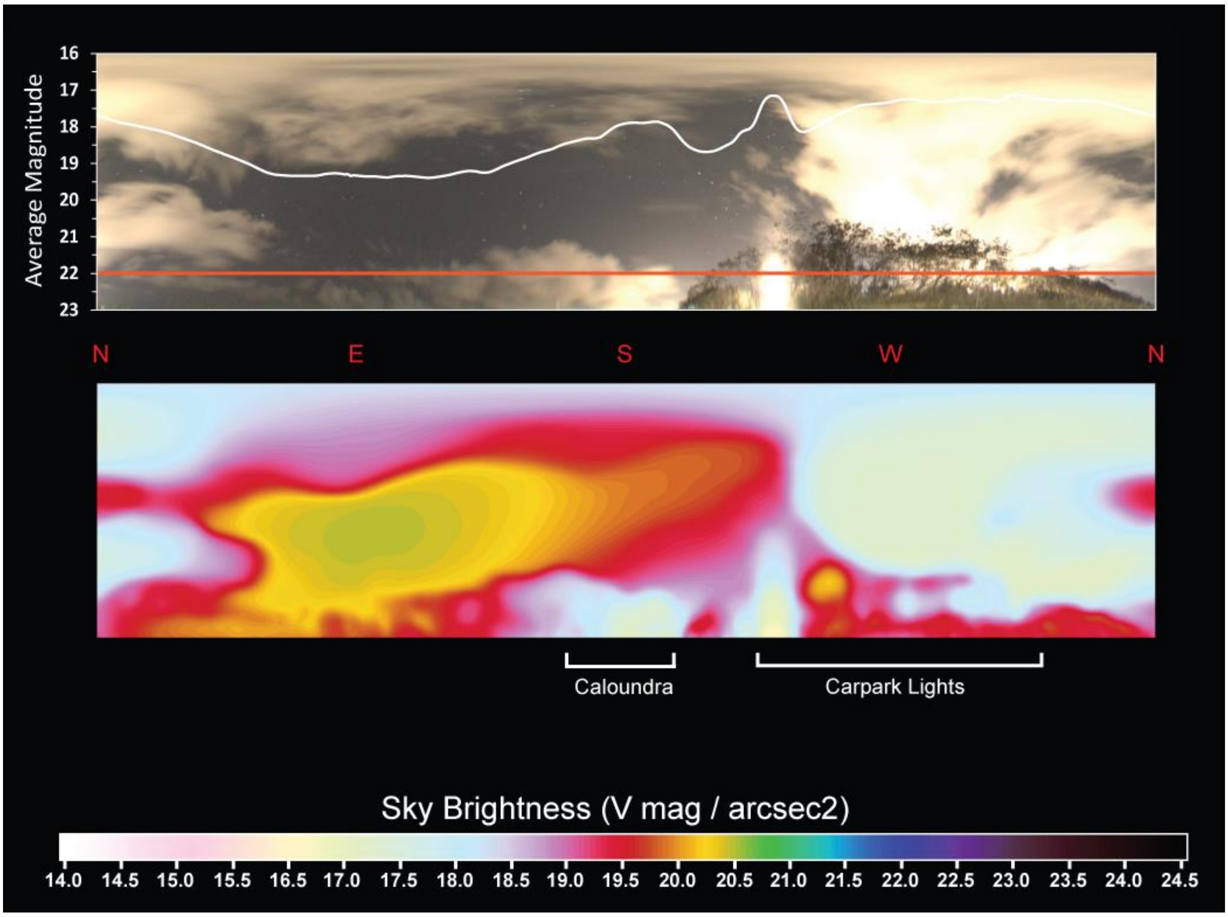



**Figure 20: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Coopers Lookout/Kawana SLSC beach, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

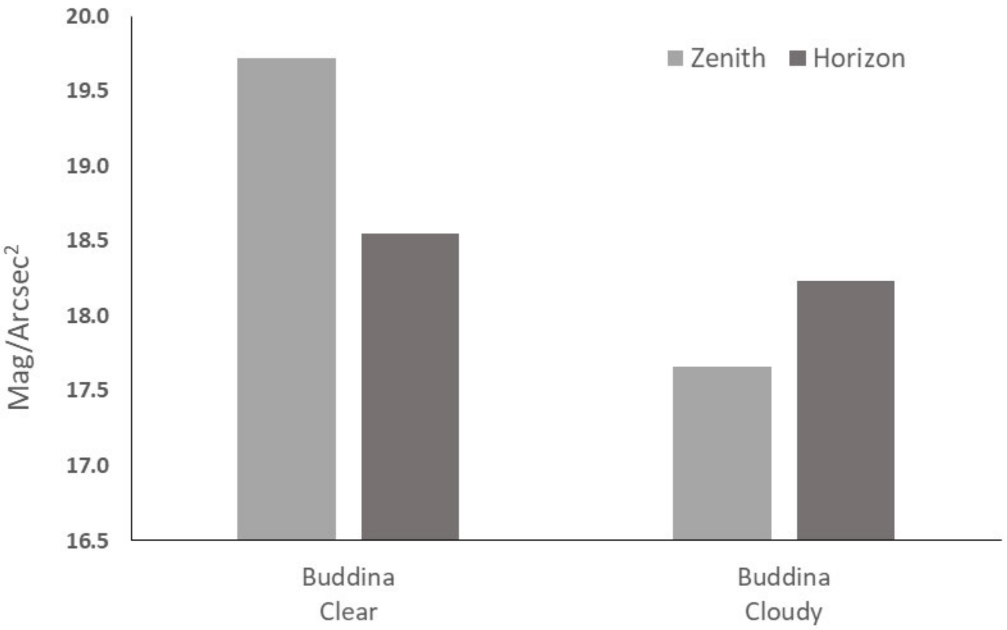



**Figure 21: Horizon and zenith magnitude/arcsec$^2$ values at Buddina Coopers Lookout/ Kawana SLSC with all lights on i.e. no modification of the current lighting regime, on a (left) clear night and (right) cloudy night.**

#### 3.2.5.3 Coopers Lookout/Kawana SLSC - Lighting Scenarios A and B

A trial to quantify different lighting scenarios was conducted at this site on the night of 25$^{th}$ June 2017. The two scenarios were;

- Scenario A: The new, recently installed, parking lot lights (LEDs) turned off and only the old parking lot lights (which had amber filters fitted) turned on; and
- Scenario B: all carpark lights, including old and new recently installed lights, were turned off.

Lighting Scenario B was captured 15 – 20 minutes after Scenario A. In that time some low-lying cloud had drifted across the sky and into the survey zone and therefore this image is representative of a partially cloudy night.

#### 3.2.5.3.1 Cooper's Lookout/Kawana SLSC – Lighting Scenario A

Average 'whole of sky' magnitude from the monitoring site at Coopers Lookout/Kawana SLSC on a clear night when the new carpark lights were switched off and the old carpark lights were left on, was 19.80, zenith was 19.93 and the horizon was 19.19 (**Figure 22**).

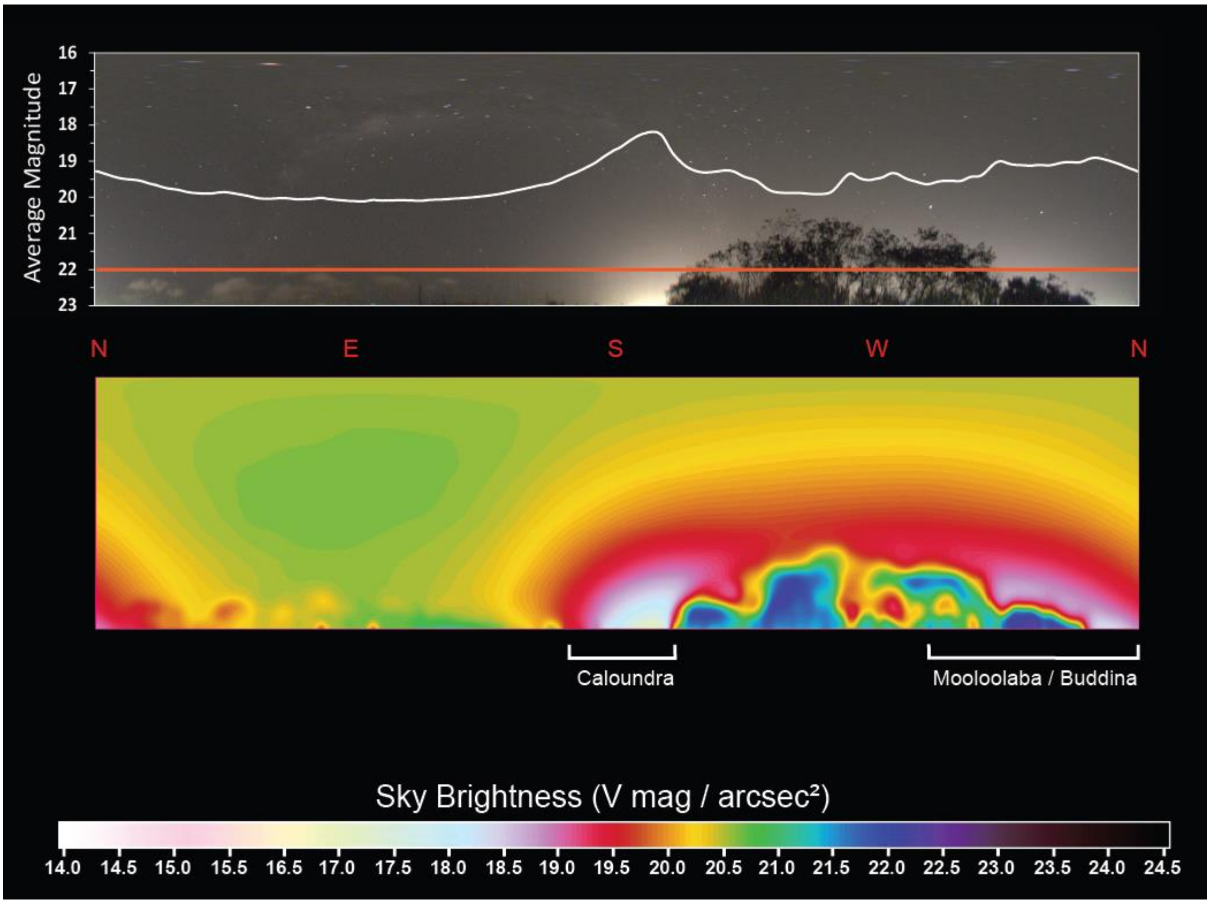



**Figure 22: Scenario A: bearing (°) and average magnitude in clear sky conditions where the main carpark lights were turned off, measured in June 2017 from Coopers Lookout/Kawana SLSC beach, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.5.3.2 Cooper's Lookout/Kawana SLSC – Scenario B

Average 'whole of sky' magnitude from the monitoring site at Coopers Lookout/Kawana SLSC on a clear night with partial/sparse cloud cover when both old and new carpark lights were switched off was 19.73, zenith was 19.92 and the horizon was 19.23 (**Figure 23**).

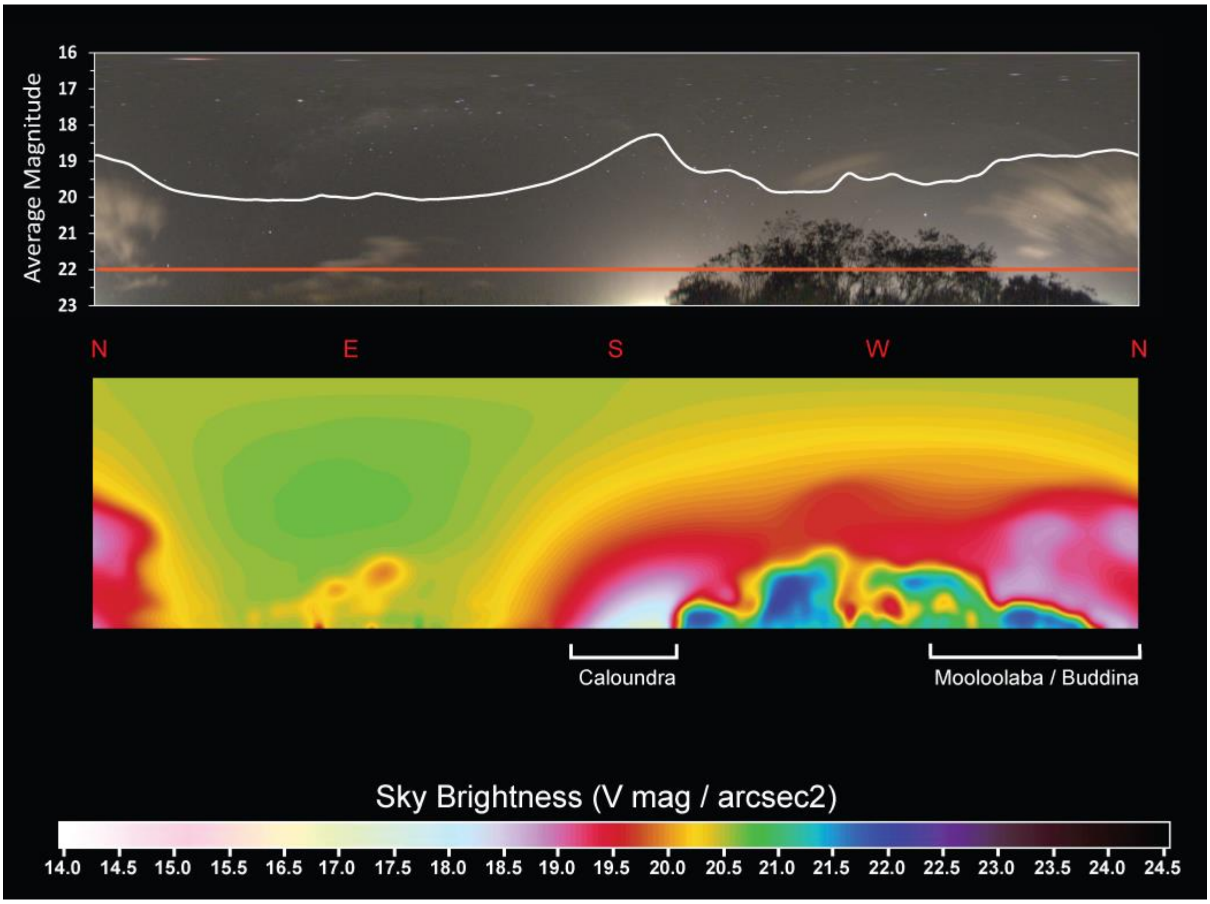



**Figure 23: Scenario B: bearing (°) and average magnitude in clear sky conditions with partial cloud cover where SLSC and all carpark lights were turned off, measured in June 2017 from Coopers Lookout/Kawana SLSC beach, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.6 Point Cartwright - clear

Average 'whole of sky' magnitude from the monitoring site at Point Cartwright (Access 198-200) on a clear night was 20.09, zenith was 20.19 and the horizon was 19.05. **Figure 24** shows many localised peaks in brightness attributed to individual point sources of light located in the carpark at Point Cartwright which increases the overall value of horizon brightness. The associated dips in brightness are partially due to the nature of point source light and partially due to the shielding effect of the tall trees positioned along the clifftop. The glow in the south is from the direction of urban areas around Buddina, Currimundi, Caloundra and Brisbane. A small peak in light intensity is visible over the lighthouse in the north of the image and another over an offshore vessel in the east.

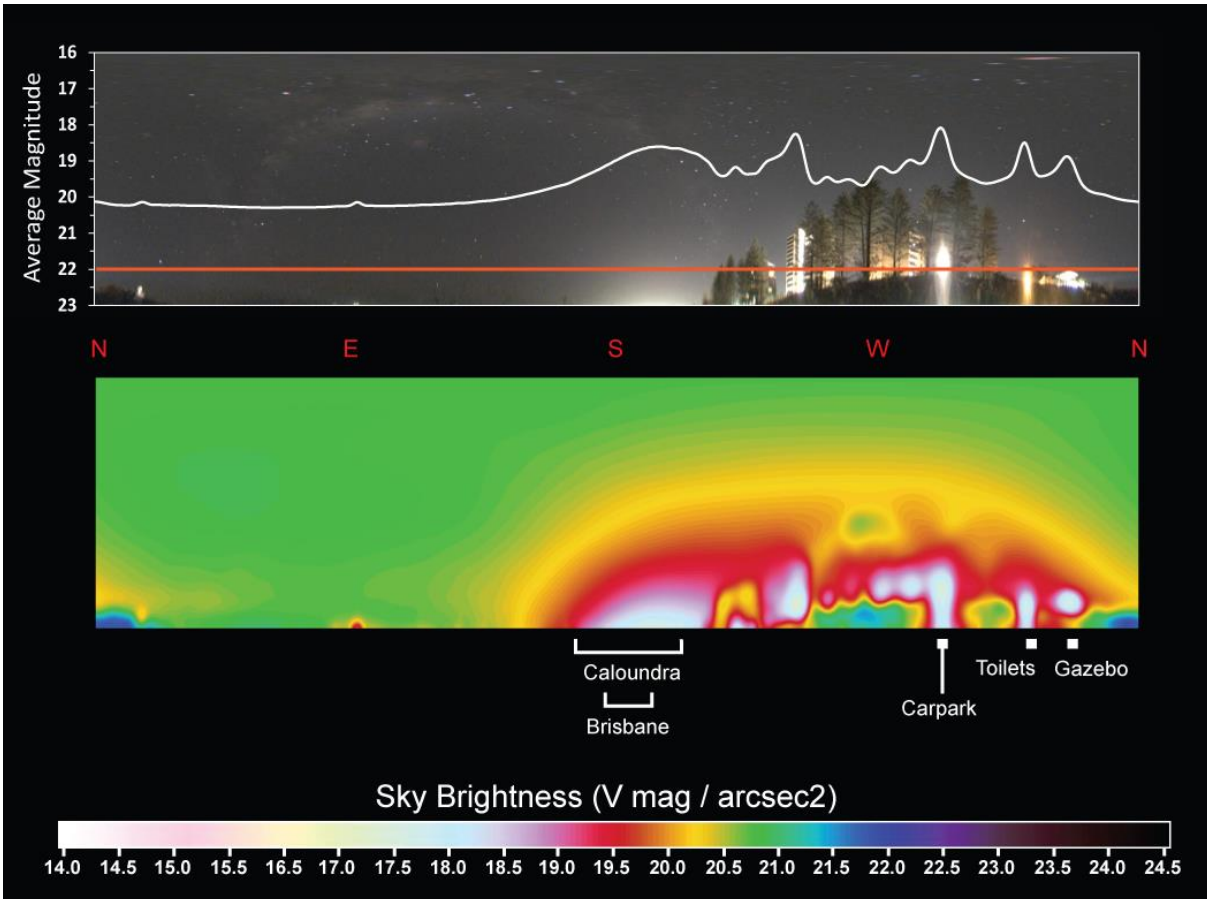



**Figure 24: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Point Cartwright beach, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.7 Mooloolaba

#### 3.2.7.1 Mooloolaba - clear

Average 'whole of sky' magnitude from the monitoring site at Mooloolaba on a clear night was 19.67, zenith was 19.77 and the horizon was 18.79. The brightest light emissions visible in **Figure 25** are unshielded point sources from the urban area north-west of the monitoring site. An orange glow in the north-west is from the direction of the Sunshine Coast and includes cumulative glow from the Sunshine Coast airport less than 10 km away and potentially also from Noosa Heads up to 30 km away on this bearing.

The peak in brightness in the south-east includes light from Point Cartwright, where several apartment buildings sit high on the cliff facing toward the monitoring site and emissions from Buddina and the urban areas further to the south along this bearing. The small localised peak in light is likely from point source light associated with a public gazebo and general lighting situated in the carpark beside the monitoring site. The dip to the south-south-west of the gazebo is due to the shielding effect of vegetation between the carpark and the camera positon.

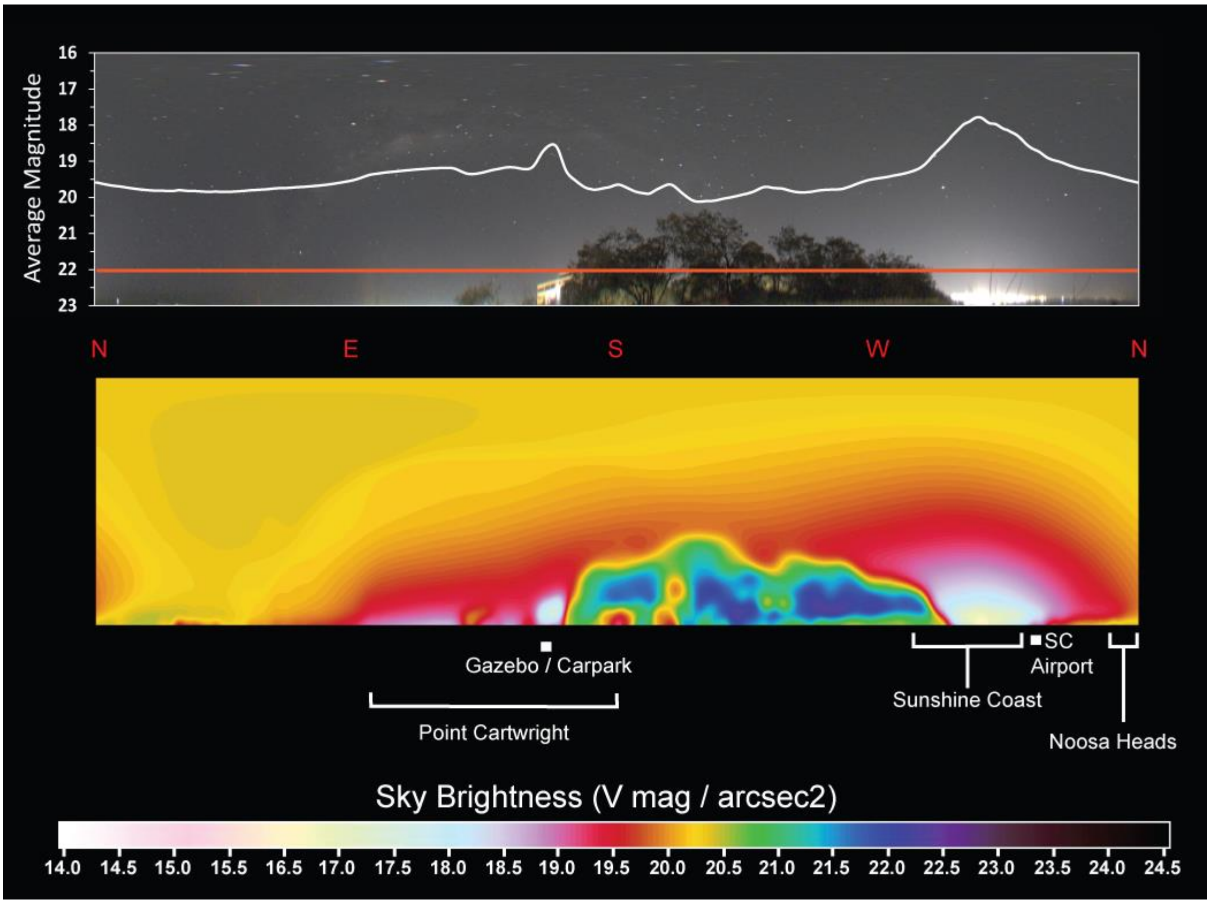



**Figure 25: Bearing (°) and average magnitude in clear sky conditions, measured in June 2017 from Mooloolaba beach, Sunshine Coast**. X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.7.2 Mooloolaba - cloudy

Average 'whole of sky' magnitude from the monitoring site at Mooloolaba on a cloudy night with near complete cloud coverage was 16.84, zenith was 16.81 and the horizon was 18.01. The effect of cloud on the amplification of sky glow is very clearly demonstrated in **Figure 26.**

The strong scattering and reflection of light from multiple sources over a broad geographic area strongly illuminates the entire sky overhead. The presence of the cloud increased zenith (overhead) sky brightness aby an order of magnitude, from 19.77 (clear sky) to 16.81 (cloudy sky). The location of specific sources are as per **Figure 24** and are noted for reference.

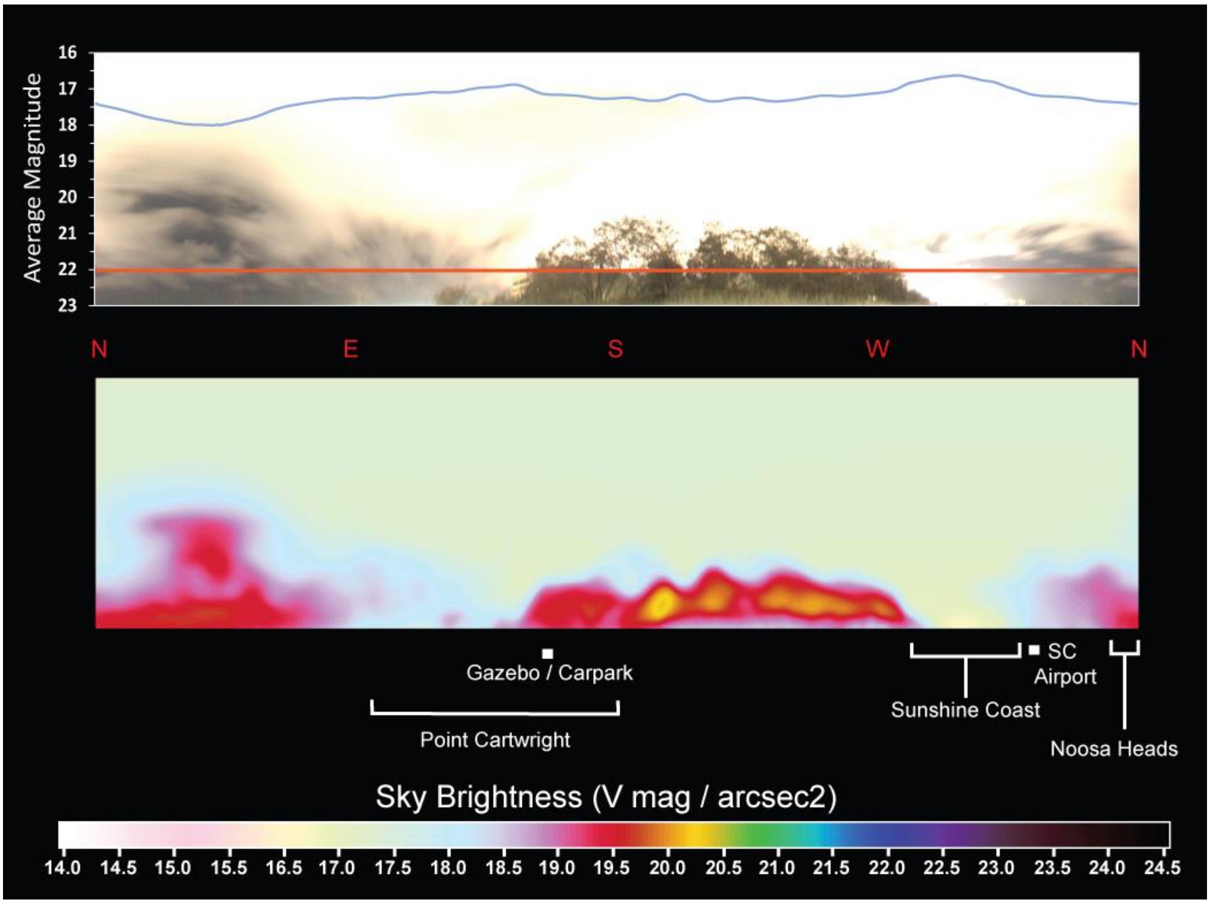



**Figure 26: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Mooloolaba beach, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.8 Mudjimba

#### 3.2.8.1 Mudjimba south – clear

Average 'whole of sky' magnitude from the monitoring site at Mudjimba – south on a clear night was 20.37, zenith was 20.51 and the horizon was 18.52. Sky glow in the north is light from Yaroomba and Coolum beach and Noosa Heads over 20 km away (**Figure 27**). The Sunshine Coast Airport and adjacent State Government Transport Main Roads roadworks project which was underway during the survey period, are located 0.5 km to the south-south west. Light from this source contributed to the peak in light emissions from this direction together with the cumulative emissions from urban areas between Mudjimba, Mooloolaba and the Sunshine Coast to Caloundra. There was a shielding effect from dense vegetation in the west of the image.

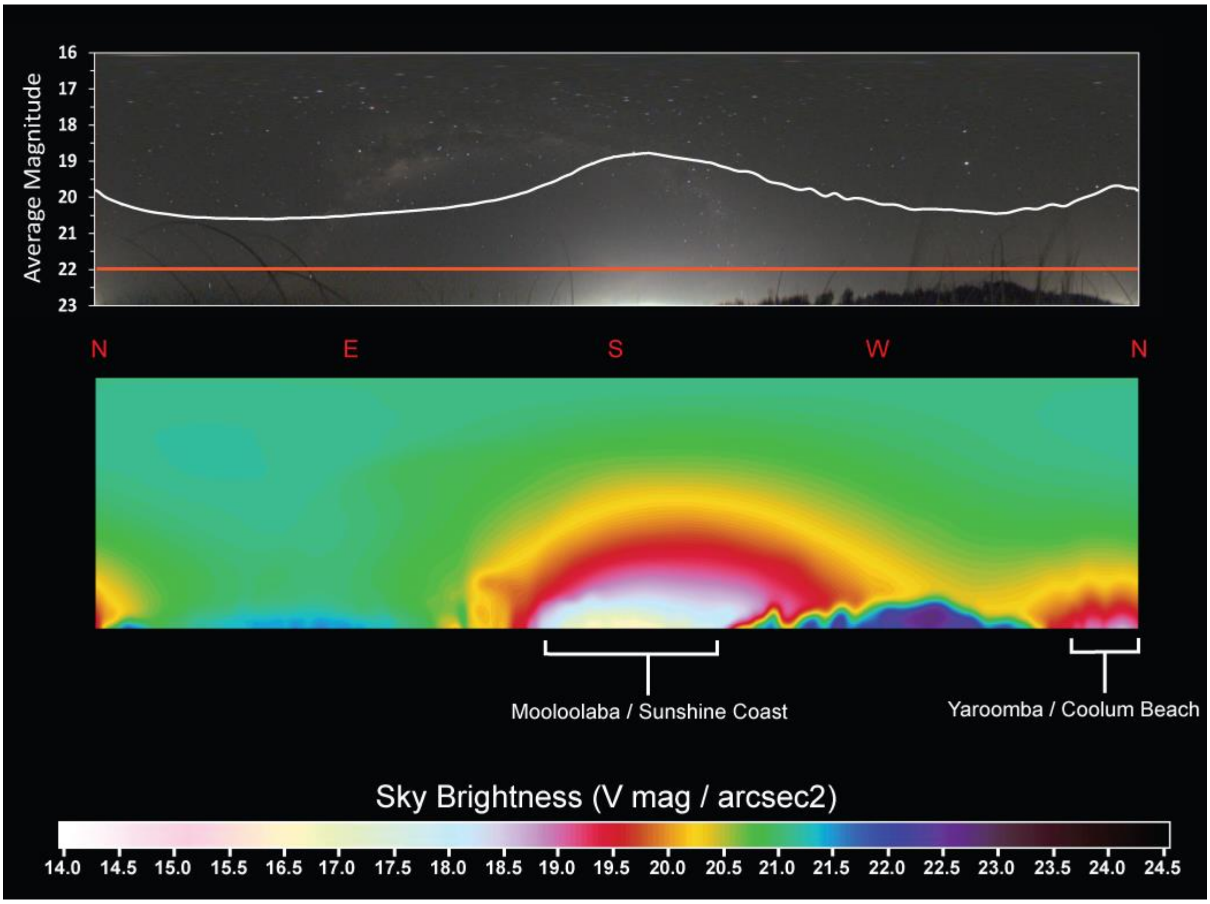



**Figure 27: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Mudjimba beach - south, Sunshine Coast**. X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.8.2 Mudjimba north – clear

Average 'whole of sky' magnitude from the monitoring site at Mudjimba – north on a clear night was 20.51, zenith was 20.64 and the horizon was 19.24. This site was close to the Mudjimba south site and the results were similar. Visible sky glow included Yaroomba and Coolum beach and Noosa Heads in the north, the Sunshine Coast Airport and adjacent roadworks 0.5 km to the south-south west and cumulative emissions from urban areas between Mudjimba, Mooloolaba and the Sunshine Coast to Caloundra (**Figure 28**). The location of vegetation behind the beach provide shielding on the horizon and is concurrent with the dip in brightness in the north-west.

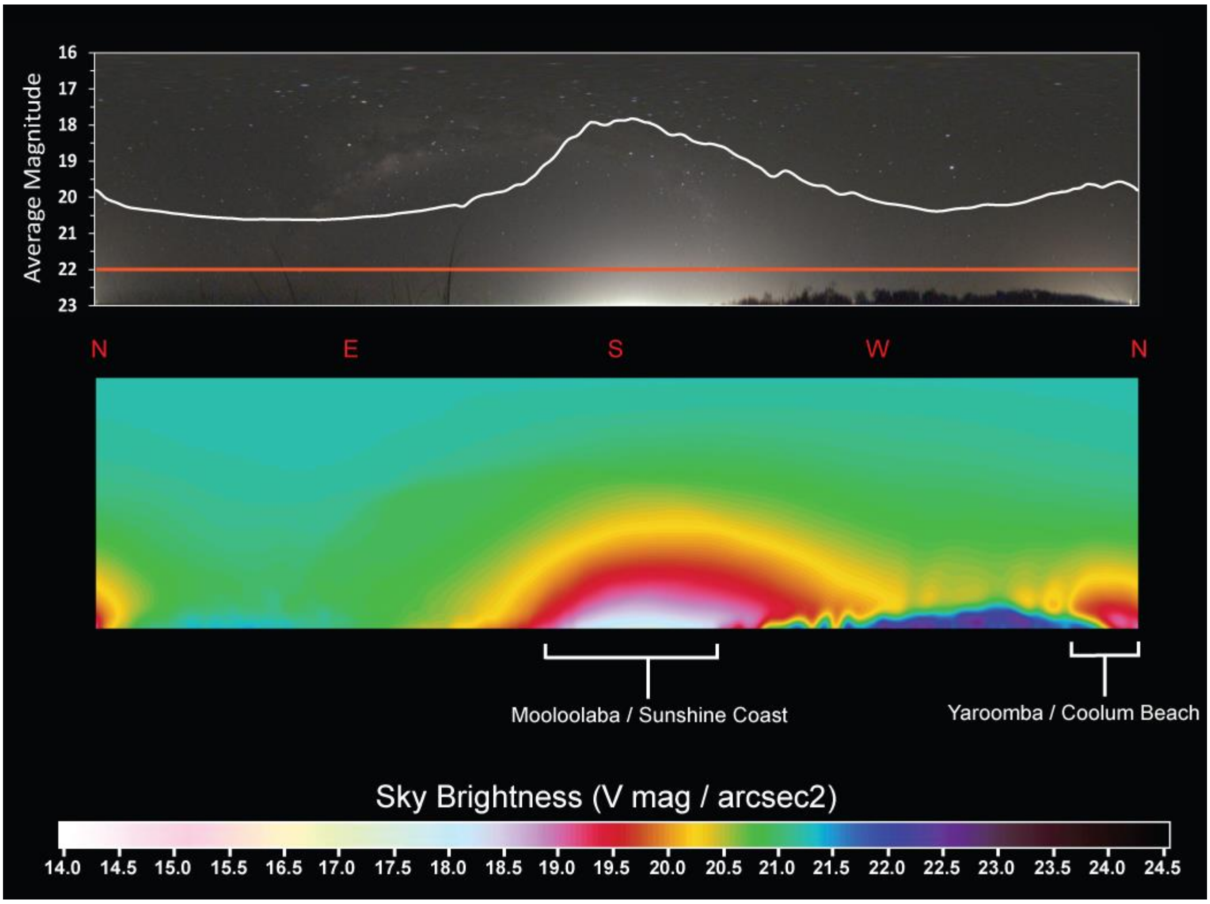



Figure 28: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Mudjimba beach - north, Sunshine Coast. X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.9 Yaroomba

#### 3.2.9.1 Yaroomba south – clear

Average 'whole of sky' magnitude from the monitoring site at Yaroomba - south on a clear night was 20.74, zenith was 20.86 and the horizon was 19.75. **Figure 29** shows peak light emissions were primarily in the south from the direction of the Sunshine Coast, Mudjimba and Mooloolaba. Glow in the north is from the direction of Coolum Beach and Noosa Heads. The dip in brightness in the west and north-west occurs in line with the vegetation screen situated behind the beach.

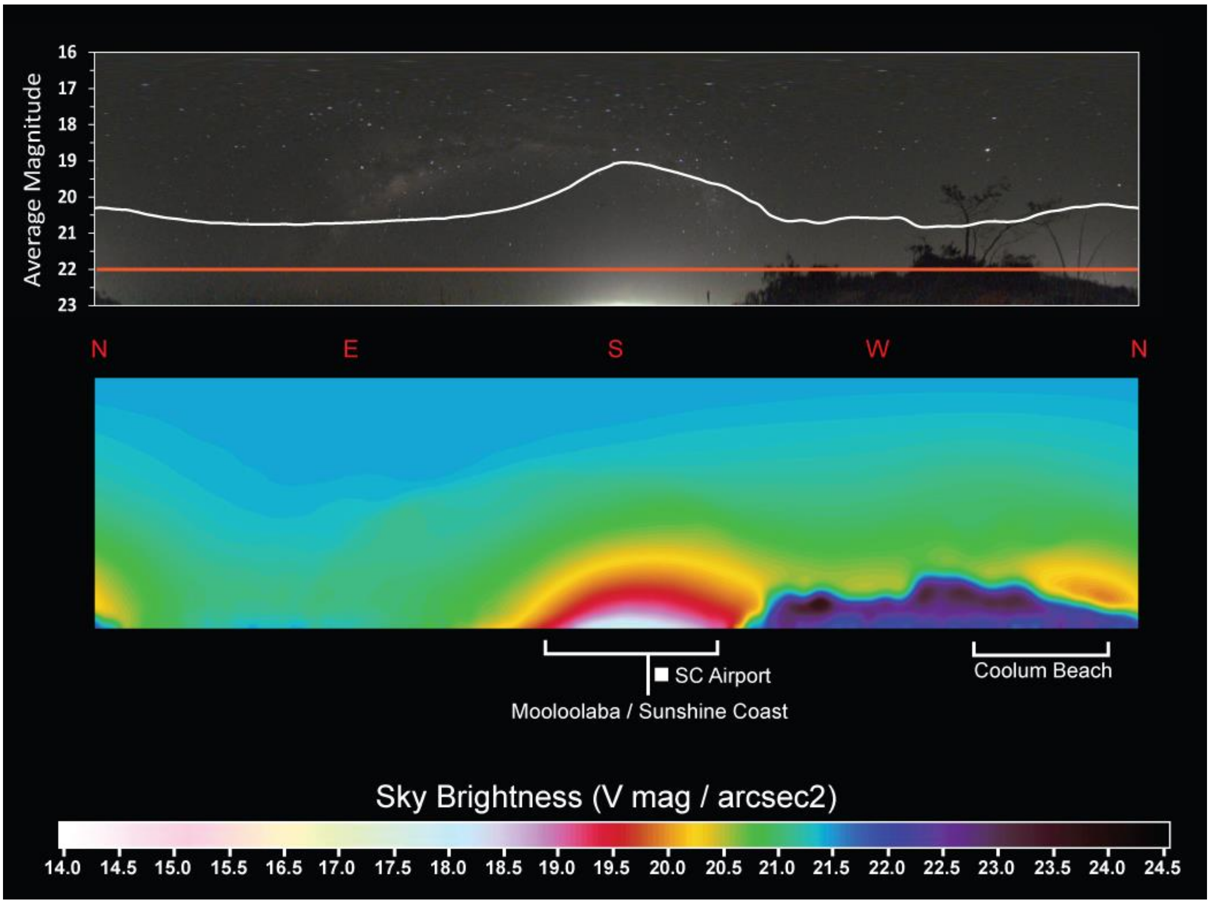



**Figure 29: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Yaroomba beach south, Sunshine Coast**. X axis: bearing from 0º - 359º, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.9.2 Yaroomba north – clear

Average 'whole of sky' magnitude from the monitoring site at Yaroomba - north on a clear night was 20.76, zenith was 20.85 and the horizon was 20.02. Visible sources of light emissions in **Figure 30** are primarily in the south from the direction of the greater Sunshine Coast urban zone and Mooloolaba. Glow in the north is from the direction of Coolum beach however the primary light source in this image noted by observers on the beach was the glow from the toilet block lights immediately adjacent to the monitoring site and partially shielded by tall trees.

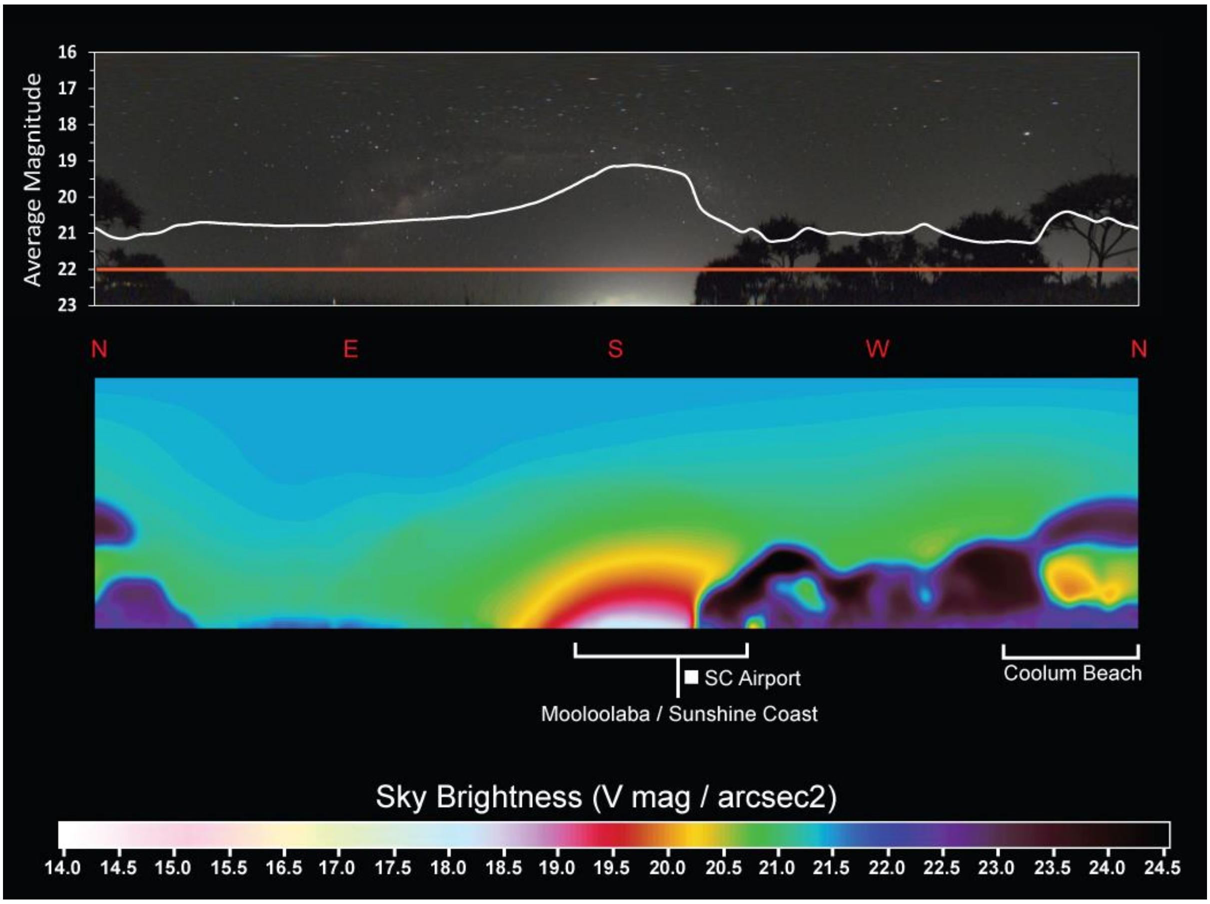



**Figure 30: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Yaroomba beach north, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

### 3.2.10 Coolum Beach

#### 3.2.10.1 Coolum Beach - south

Average 'whole of sky' magnitude from the monitoring site at Coolum beach - south on a clear night was 19.48, zenith was 19.62 and the horizon was 17.90. The bright white light in the south-west of **Figure 31** is the lights affixed to the Coolum beach SLSC and the multiple peaks of point source lights along the horizon in the west are those of public facilities in Tickle Park, Coolum Beach.

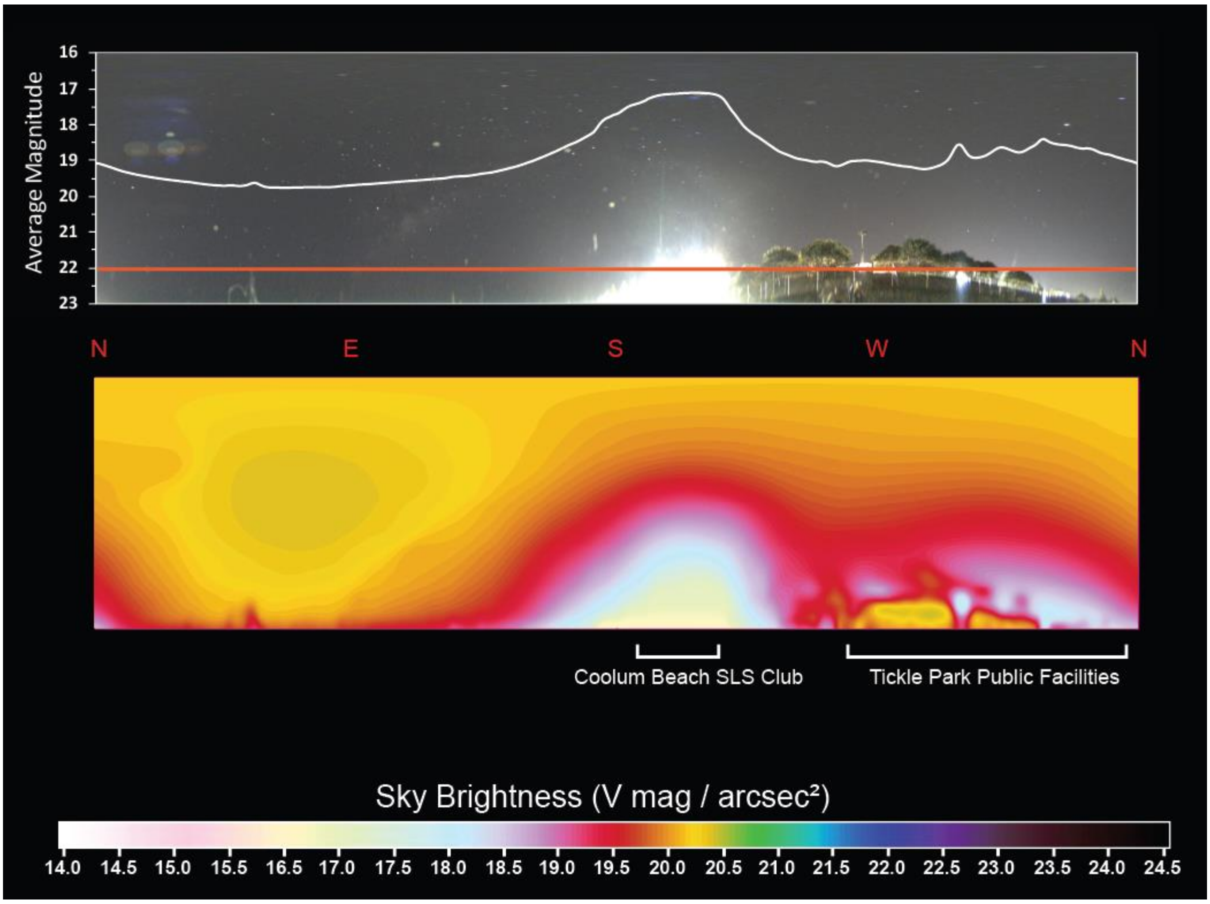



**Figure 31**: **Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Coolum Beach south, Sunshine Coast**. X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

#### 3.2.10.2 Coolum Beach - north

Average 'whole of sky' magnitude from the monitoring site at Coolum beach - north on a clear night was 20.19, zenith was 20.31 and the horizon was 19.14. The peak intensity in the south included light from urban areas between Coolum Beach, Yaroomba, Marcoola, Mooloolaba and within the greater Sunshine Coast urban zone. The glow extended to the west towards Peregian Springs and north towards Noosa Heads and included urban communities in between e.g. Peregian Beach, Marcus Beach, Castaways, Sunrise and Sunshine Beaches (**Figure 32**). Vegetation screening located to the west blocked horizon glow and reduced brightness from this direction.

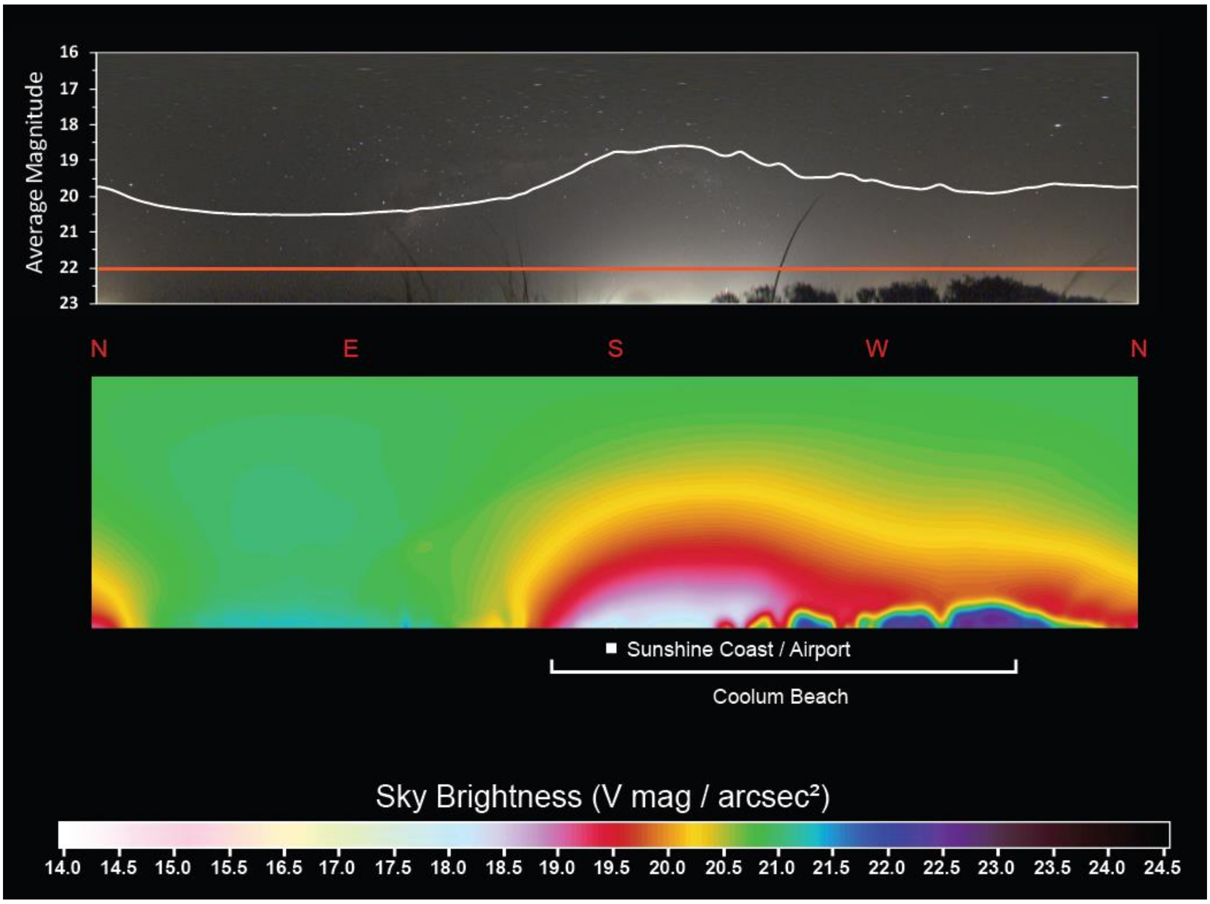



**Figure 32: Bearing (°) and average magnitude in cloudy sky conditions, measured in June 2017 from Coolum beach north, Sunshine Coast.** X axis: bearing from 0° - 359°, Y axis: average magnitude (V mag/arcsec$^2$). Red bar: 'ideal' or 'target' light level - average magnitude 22 or less.

## 3.3 Audit of Visible Point Sources of Light

An audit of visible point sources of light was conducted on 26th June 2017. The audit team positioned themselves on the access point to each monitoring beach and collected data on the bearing and estimated distance from the observer recorded to the most visible unshielded light sources (**Table 7**). Twenty individual lights/groups of lights were identified at four of the monitored beaches.

**Table 7: Lighting audit of visible point source light.** Distance (m) and height (m) are estimated values only.

| Id | Beach | Monitoring Location | Audit Location | Bearing (°) | Distance (m) | Height (m) | Colour | (*n*) | Structure | Description |
|---|---|---|---|---|---|---|---|---|---|---|
| - | Coolum | North | Monitoring site | NA | NA | NA | NA | NA | NA | No visible lighting structures |
| - | Yaroomba | North | Monitoring site | NA | NA | NA | NA | NA | NA | No visible lighting structures |
| - | Yaroomba | South | Monitoring site | NA | NA | NA | NA | NA | NA | No visible lighting structures |
| 1 | Mudjimba | North | End access pathway | 350 | 1000+ | 3 | White | 1 | Light pole | Street light on road side of trees |
| 2 | Buddina | Point Cartwright | Top of access steps in carpark | 290 | 23 | 3 | Orange | 1 | Light pole | Near to toilet block in carpark |
| 3 | Buddina | Point Cartwright | Top of access steps in carpark | 230 | 20 | 3 | White | 1 | Light pole | Carpark light |
| 4 | Buddina | Point Cartwright | Top of access steps in carpark | 320 | 26 | 2 | White | 3+ | Toilet block | Exterior to toilets, interior of structure, fluorescent bulbs |
| 5 | Buddina | Cooper's Lookout | Top of access steps (221) in carpark | 300 | 20 | 6 | White | 1 | Light pole | Carpark lighting, LEDs, (**Figure 33**) |
| 6 | Buddina | Cooper's Lookout | Top of access steps (221) in carpark | 270 | 30 | 6 | White | 1 | Light pole | Carpark lighting, LEDs |
| 7 | Buddina | Cooper's Lookout | Top of access steps (221) in carpark | 220 | 25 | 6 | White | 1 | Light pole | Carpark lighting, LEDs |
| 8 | Buddina | Cooper's Lookout | Top of access steps (221) in carpark | 200 | 70 | 6 | White | 1 | Light pole | Carpark lighting, LEDs |
| 9 | Buddina | Cooper's Lookout | Top of access steps (221) in carpark | 190 | 70 | 6 | White | 1 | Light pole | Carpark lighting, LEDs |
| 10 | Buddina | Cooper's Lookout | Top of access steps (221) in carpark | Directly above | 0 | 6 | White | 1 | Light pole | Carpark lighting LEDs |
| 11 | Buddina | Cooper's Lookout | Top of access steps (221) in carpark | 180 | 65 | 3 | White | 3+ | Light pole | Carpark lighting LEDs |
| 12 | Mooloolaba | NA | Bottom access step to carpark | 220-240 | 30 | 2 | White | 16 | Gazebo | 8 banks of 2 bar fluorescent bulbs underneath roof of gazebo |

| Id | Beach | Monitoring Location | Audit Location | Bearing (°) | Distance (m) | Height (m) | Colour | (*n*) | Structure | Description |
|---|---|---|---|---|---|---|---|---|---|---|
| 13 | Mooloolaba | NA | Bottom access step to carpark | 210 | < 50 | 1 | White | 1 | Light pole | Fluorescent street light pole /carpark lighting |
| 14 | Mooloolaba | NA | Bottom access step to carpark | 110-120 | <50 | 3 | White | 3 | Light pole | Fluorescent street light pole /carpark lighting |
| 15 | Currimundi | NA | Monitoring site | NA | NA | NA | Na | NA | NA | No visible lighting structures |
| 16 | Shelly Beach | South | End of William St | 270 | 230 | 3 | White | 1+ | Light pole | Street lighting* |
| 17 | Shelly Beach | South | End of William St | 270 | 200 | 3 | White | 1+ | Light pole | Street lighting |
| 18 | Shelly Beach | South | End of William St | 40 | 270 | 3 | White | 1 | Light pole | Street lighting** |
| 19 | Shelly Beach | South | End of William St | 40 | 290 | 3 | White | 1 | Light pole | Street lighting cnr William St and Ocean Court |
| 20 | Shelly Beach | North | Post 25 | [redacted] | | | - | 1 | [redacted] | |

*Corner of William Street and Wellington Street and all lights up William Street which are highly visible from this location. William Street rises away from the beach so each light equally visible even though distance from beach increases **Corner of William Street and Ocean Court these lights have highly visible emissions. Suggest lowering them, shielding them, moving them to further down Ocean Court behind the houses so they are screened by the dense vegetation.

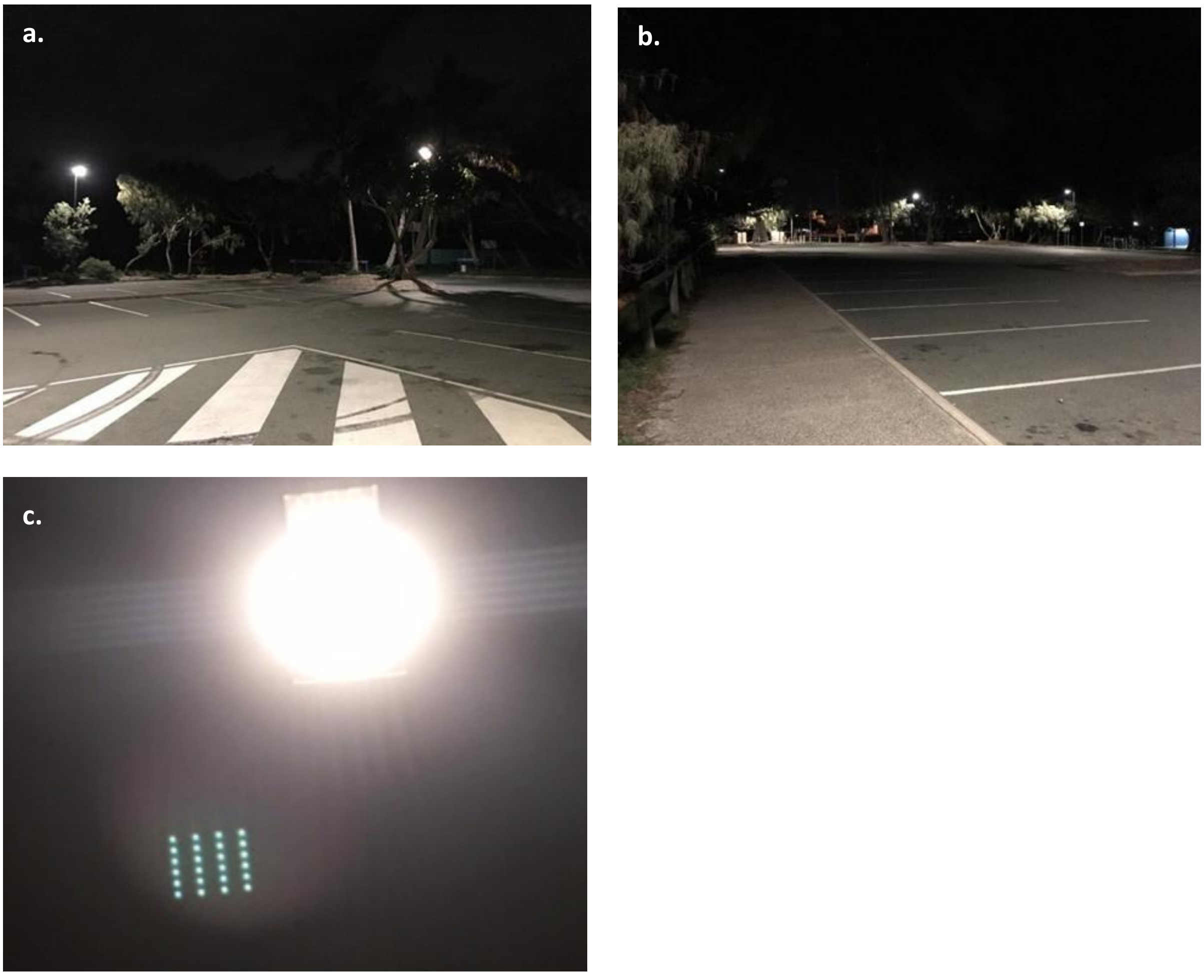



**Figure 33: Lighting in car park at Buddina Coopers Lookout/Kawana SLSC** a. looking away from the beach toward the road; b. looking south toward the SLSC and toilet block (on right of image) and c. close up of an indicative LED lighting fixture located at top of access (221) steps, taken from 2 m away. See **Figure 18** for isophote image of lighting from the nesting beach immediately adjacent to this location.

# 4 DISCUSSION

This report quantifies for the first time 'benchmark' levels of night-time illumination visible from key marine turtle nesting beaches on the Sunshine Coast and South Bribie Island in Queensland. Levels of artificial light varied among locations from those considered representative of darker, rural areas to those typical of a night sky horizon modified by the presence of artificial light.

The survey period was scheduled outside the marine turtle reproductive season, which encompasses a period of approximately four months from November to March each year. On each survey night, Sky42™ captured up to five images at approximately five minute intervals at each location. The approach therefore captured light profiles over a deployment period of up to thirty minutes at each site and it should be recognised that both natural and artificial light profiles are variable throughout the night (particularly at busy, public beaches) and from night to night throughout the year, at all locations.

Specific events and facilities that should be considered when reviewing data presented within this report include the airport, roadworks and school holidays. Lighting associated with regional airports is, by its nature, detectable over long distances (e.g. apron mast lighting) contributing to cumulative regional sky glow. There were Department of Transport and Main Roads night time roadworks active in the Mudjimba area during the survey period and the school holiday period began on Friday 24th June 2017. Whether or not school holidays impacted Council lighting management in public areas is not known but may have increased night-time usage and therefore lighting in some public areas.

Hatchlings follow three primary cues when sea-finding; movement toward brighter regions on the horizon, movement away from tall dark beach silhouettes (e.g. dunes and tree lines) and when these cues are inconsistent, movement in relation to elevation (Bartol & Musick 2003; Limpus 1971; Salmon et al. 1992; Limpus & Kamrowski 2013; Pendoley & Kamrowski 2015).

Artificial light is, therefore, one of several competitive visual stimuli that hatchlings must integrate with natural light intensity, wavelength, directivity, and horizon/elevation cues to navigate successfully toward the ocean. A high, dark silhouette at an elevation of 16° provides an adequate cue against which hatchlings have can orient seaward, even in the presence of overhead sky glow (Pendoley & Kamrowski 2015). These requirements are met by vegetation on the dune profile, for example tall trees that reach the approximate height of a one or two story apartment building.

Adult turtle behaviour is also affected on brightly lit urban beaches. Deterred from nesting in brightly, lit areas, female turtles will nest preferentially in the darker areas in front of tall buildings or in front of vegetation such as tall trees (Salmon et al. 1995).

The importance of vegetation at the nesting beach cannot be over stated. Vegetation on the dune profile play two key roles in light management: as a shield, reducing the amount of light at the horizon level that directly reaches the beach and in creation of a tall dark horizon at the appropriate elevation. Suitable vegetation screening was noted in some sections of images at 12 of 16 sites in this survey. Of note were Woorim (south) from south to north, Shelly beach (north) south-west to north, Currimundi from south to west and Yaroomba south-west to north.

Screening at Shelly beach (north) can be usefully compared to the southern site on the same beach located 150 m to the south. Subject to similar light profiles, both zenith and whole-of-sky brightness were similar (maximum variation between sites: 0.05 mag/arcsec$^2$). At the horizon level however, the northern site was 0.27 mag/arcsec$^2$ darker than the southern site. At Shelly beach (north) there was a dense vegetation screen which shielded the beach in front from direct light. Shelly beach (south) was located adjacent to a revegetation zone and consequently there was no vegetation to shield light.

Climate change is expected to drive changes in habitat conditions over a range of coastal environments, increasing temperatures and affecting shoreline erosion, advancing beach loss, and modifying tidal systems. Warmer temperatures will expand the current nesting range of turtle populations focused around rookeries further north into the sunshine coast region. Planting trees and vegetation on the dune profile and maintaining existing vegetation is critical to the maintenance of suitable nesting habitat. Trees will shield the beach from light, supporting adult nesting and providing a dark horizon to facilitate successful ocean finding in hatchlings, stabilize the dune profile providing protection from rising sea levels and modification of tidal systems and provide shading to cool sand temperatures thus minimizing potential impacts of temperature change on sex-ratios.

The primary source of sky glow was from towns and cities located along the coastline, with additional glow from the Sunshine Coast Airport and roadworks. Specifically, glow from Brisbane, was visible from Bribie Island and Caloundra and is likely to be contributing to the sky glow visible from beaches along the Sunshine Coast albeit at lower intensity levels than more localised light sources.

The extended urban zone between Pelican Waters in the south and Mooloolaba in the north cumulatively contributes a substantial amount of light to the sky glow over the Sunshine coast which is detectable from the southern end of Bribie Island in the south to Coolum in the north. On a local scale, street light and most commonly, car park lighting, increased brightness where they were located adjacent to the nesting beach. There were no offshore sources of lighting detected in this survey.

In all instances, the presence of cloud increased sky glow brightness and where low heavy cloud intersected brightly lit areas the increase in sky glow was substantial (e.g. Buddina Coopers Lookout/Kawana SLSC with LED lights on). This increase in sky brightness not only occurred when the clouds were directly overhead but also increased the visibility of sky glow on the horizon when the clouds were located above a geographically remote light source. For example from Bribie Island, the lights of Brisbane are visible on the horizon in **Figure 10** when there are clouds over Brisbane reflecting the light back to the earth and the lights of Caloundra are more visible in the north of **Figure 11** due to cloud cover over the area.

The SCC has confirmed that to date ~3% of street lights in the region are LEDs, however there are council plans to embark on a large regional conversion program in the near future. Recognising the potential for glare and public discomfort from very bright white LEDs, the council has proposed a 3000K CCT limit on the LED street lighting. While this low CCT meets the recommendations of the International Dark Sky Association it is important that the lights be managed to reduce upward light spill and glare and that the LEDs contain as little blue wavelength light as possible, to protect both marine turtle nesting and hatchling behaviour and human health. We strongly recommend that lights in any areas close to marine turtle nesting beaches are amber LEDs at the minimum wattage required to protect public safety.

The following sections discuss the lighting issues observed during the survey on a site by site basis. Due to the varying and irregular qualities of cloud cover, values discussed below are those for images and data captured on clear nights only, unless otherwise stated.

**Whole of sky brightness**

The brightest (clear sky) whole of sky values fell within the 19 – 20 mag/arcsec$^2$ band, typical of a suburban night sky, and were those sites located next to excessive carpark lighting (Coopers Lookout/Kawana SLSC), an active SLSC, restaurant, public carpark and public recreation complex with lit basketball courts (Coolum beach south) and Mooloolaba beach, noting the effect of cloud on overall brightness at this location.

Buddina (Point Cartwright), with a value of 20.09 mag/arcsec$^{2,}$ at could also be included in this bright suburban category due to the very close and intense point sources of high rise and car park lighting. The close proximity and elevation of the lights on the clifftop reduces the capture of broad scale sky glow. Whole of sky brightness at all other locations was an order of magnitude less bright, falling well within the 20 – 21 mag/arcsec$^2$ range, considered a 'typical rural night sky horizon'.

**Zenith**

The darkest monitoring site was South Bribie Island – Woorim beach south where sky brightness directly overhead, at Zenith, was 21.04 mag/arcsec$^2$. The brightest zenith values were recorded at Coopers Lookout/Kawana SLSC, Mooloolaba and Coolum beach – south, with values within 19 – 20 mag/arcsec$^2$ on clear nights, associated with the highly visible street lights, high rise buildings and public facilities situated adjacent to the monitoring site. The bright point sources of light from these sources also contributed to a zenith sky brightness at the very low end of the rural sky range and close to the suburban sky range at Buddina, Point Cartwright.

**Horizon**

At the horizon level, in the visual zone favoured by hatchlings during sea finding, the brightest monitoring site across the entire survey was at Coolum south. Brightness measured 17.90 mag/arcsec$^2$; these high values are representative of a "poor urban night sky".

High light levels representative of a "typical urban night sky" were observed at South Bribie Island, Woorim beach mid (public carpark), Buddina Coopers Lookout/Kawana SLSC (public carpark with LED lights turned on), Mooloolaba and Mudjimba south (airport). Measured light at these locations was within 18 – 19 mag/arcsec$^2$.

Other moderately bright monitoring sites, representing a "typical suburban sky" (19 – 20 mag/arcsec$^2$ range), included North Bribie Island (Lions Park), Shelly Beach North and South, Currimundi, Buddina Coopers Lookout/Kawana SLSC (public carpark with LED lights turned off), Buddina Pt Cartwright, Mudjimba North, Yaroomba south and Coolum North.

The least light polluted sites were found at Woorim north and south and Yaroomba north which were characterised by low light levels representative of a typical rural sky (20 – 21 mag/arcsec$^2$).

**Current Artificial Light Profiles**

*South Bribie Island – Woorim beach (south)*. The brightest location visible from this monitoring site was Brisbane, located to the south. At approximately 200° almost exactly along the bearing of Brisbane City, the increasing sky brightness dips visibly. This is due the shielding effect of the trees located along the back of the beach, decreasing the amount of light from the City that reaches the beach at this location.

*South Bribie Island – Woorim beach (mid)*. This is the most utilised public section of the beach, directly in front of the carpark. Light from Brisbane in the west was still visible as glow behind the carpark and the light associated with specific lighting fixtures located close to the monitoring site were highly visible from the monitoring site.

*South Bribie Island – Woorim beach (north).* From this location the horizon appeared dark with the exception of light from Caloundra in the north – emphasised in the image due to several small patches of low-lying cloud along the bearing over the town.

*North Bribie Island – Lions Park.* Light from Pelican waters and Golden Beach is visible as glow in the west of the image and Brisbane can be seen in the south.

*Shelly beach – south.* Shelly beach has been identified by Dr Colin Limpus as the Index Beach for the Sunshine Coast region and has been monitored since 2005. This monitoring site was located in front of a cleared area currently zoned for revegetation with several residential properties located behind it. Several streetlights located from the corner of William Street and Ocean Court up to the corner of William Street and Wellington Street were either clearly visible or visible as glow from the nesting beach. [redacted] See **Table 6** for detail regarding specific lighting fixtures.

*Shelly beach – north*. This site was located in front of dense vegetation which forms a natural barrier and shield, preventing light emissions from residential properties located immediately behind it from reaching the beach. While both zenith and whole of sky brightness at this location was very similar to that measured at Shelly beach south, horizon level brightness (i.e. light at beach level) was half a magnitude band less bright than at the southern site where vegetation had been cleared. These results demonstrate the value of vegetation screens in providing an elevated dark horizon behind the beach, a characteristic that has been shown to be critical to the successful orientation of hatchlings during sea-finding (Pendoley and Kamrowski, 2015).

*Currimundi beach.* There were no specific point sources of light visible from this monitoring location. There was a white glow visible in the south from Caloundra and over a greater distance, from Brisbane. Glow from the greater Sunshine Coast urban zone could be seen in the north.

*Buddina - Coopers Lookout/Kawana SLSC.* The major sources of light at this site included a SLSC, toilet facilities, and a carpark which was recently subject to a carpark lighting modification program, including the installation of new LED lighting in addition to the existing carpark lights and new lights installed at the top of the beach access stairs. Light emissions at this site were noticeably brighter than under the old lighting regime. Under the influence of clouds, sky brightness increased by two orders of magnitude from 19.72 mag/arcsec$^2$ to 17.66 mag/arcsec$^2$, an increase in zenith sky brightness of ~ 566 % (Kyba et al. 2011). In contrast, the increase in horizon brightness was 34 %, the reflective qualities of sand dunes, and in particular trees, being less than that of clouds (**Figure 20**).

*Buddina - Coopers Lookout/Kawana SLSC Scenario A.* These results quantified the light from the old car park lights and the Surf Life Saving Club only under clear skies. Extinguishing the new LED car park lights produced a decrease in sky luminance of ~16 % at zenith and approximately 40 % at the horizon.

*Buddina - Coopers Lookout/Kawana SLSC Scenario B*. The final dataset at this location captured images with no lights on at all; the Surf Club lights and the old and new LED car park lights were all turned off. The decrease in zenith luminance was less than the decrease in Scenario A (~15 % decrease) and this is thought to be due to the light cloud which moved overhead while the images were being made, increasing the sky glow detectable from other nearby urban areas.

The decrease in the horizon values when all lights were extinguished was also similar to the results from when the Surf Club lights and the old car park lights were turned on. The horizon value is less influenced by clouds and so these results suggest that the SLSC and the old car park lights do not contribute as much light to the horizon sky glow as the newly installed bright white LED lights.

The new LED technology is increasingly being used by councils globally to replace street and car park lighting due to the low maintenance and operating costs and potential for previously impossible Smart Controls on the individual light fixtures (e.g. dimming, timers, colour control, remote control etc.). While these Smart Controls will eventually provide a valuable tool to precisely manage public lighting they are still relatively new and globally Engineering Standards and Council Ordinances for the use and management of the lights have not yet been fully developed.

Bright white LED lights emit a high proportion of short wavelength blue light, the light that is most attractive to marine turtle hatchlings. This short wavelength light is strongly scattered and reflected in the night sky and for this reason it is strongly recommended that shielded amber LED lights be used in the vicinity of marine turtle nesting habitat. Amber LED light is a monochromatic light emitting at ~590 nm.

*Buddina – Point Cartwright.* Light at this location largely originates from carpark and public lighting located along the walkways, pathways and at the toilet block above the monitoring site. There is potential for considerable emissions from carpark lighting and apartment complexes located on the cliff above the beach to increase overall sky glow over the area and adjacent beach. Due to building design however (apartments/units built facing to the west, away from the beach, looking over the marina) together with topographical elevation (high cliff line, tall tree line), little light from these units is directly visible from the beach. See **Table 6** for detail regarding specific lighting fixtures.

*Mooloolaba.* Light captured at the Mooloolaba monitoring site originated from the Mooloolaba urban area located adjacent to the beach survey site and public facilities located immediately east and behind the monitoring site. A gazebo in the carpark featured several fluorescent strip lights (see **Table 6**). At this monitoring site, on the third monitoring night, overall brightness from these sources in combination with very low-lying cloud accompanied by light drizzle changed the light profile dramatically (**Figure 22**), brightly illuminating the overhead sky.

*Mudjimba – south*. Sky glow intensity at this location was greater than at Mudjimba north. The Sunshine Coast Airport is located within one kilometre of the monitoring site and road works were underway along the length of the road behind the beach. Aerial photography indicates several resorts or large high rise apartment complexes are situated behind the vegetation screen at this location. This section of beach is protected by dense vegetation which blocks direct light emissions, diminishing the amount of light that reaches the beach. The vegetation cannot, however, shield the beach from sky glow above the tree line, generated by the (temporary) airport construction works and potentially including residential buildings along the beach front and the Sunshine Coast Airport. The presence of the tree line screen is beneficial to hatchling marine turtles in that it elevates the dark horizon behind the beach providing the hatchlings with a cue to use during sea finding (Pendoley & Kamrowski 2015). Glow from the greater Sunshine coast urban area between Mooloolaba and Caloundra is also visible from this relatively rural location. Roadside lighting (a single light pole) was also directly visible from the beach.

*Mudjimba – north.* This site was located close to Mudjimba – south monitoring site and immediately north of the Sunshine Coast Airport. As was found at Mudjimba south, the heavy vegetative screen provides a natural horizon elevation cue for hatchlings during sea-finding despite the considerable sky glow that is visible above the tree line, originating from the Airport and nearby road work and from the more distant Sunshine coast urban area. The glow from Yaroomba and Coolum beach and 7 – 10 km to the north, and Noosa Heads, 21 km away is also visible on the horizon at this site.

*Yaroomba – south.* The brightest feature at this location was horizon level glow in the south from the Sunshine Coast (15 - 28 km away) visible along the length on the beach. The Sunshine Coast Airport, 6 km to the south contributed a substantial amount of light to the local sky glow. Glow from the urban area located west and to the north (at Coolum Beach) of the monitoring site was blocked at the horizon by a vegetation screen.

*Yaroomba – north.* The light profile at this location is similar to that of Yaroomba south with the primary difference being additional glow in the north of the image from the toilet block located in the carpark above the cliff. The glow was barely visible to observers at the beach level, the carpark and public facilities being located up on the cliff and screened by tall trees and dense vegetation. Without the vegetation screen, lighting from these facilities would reach the nesting beach, potentially altering the light horizon.

*Coolum beach – south.* The site was selected specifically to quantify the amount of light emitted from the large number of bright uncontrolled light sources present at the monitoring site. The image was captured immediately in front of the SLSC which had bright unshielded flood lights shining directly onto the beach, and adjacent to carpark and public walkway lighting and lighting at public recreation facilities (e.g. basketball courts) which were highly illuminated by multiple flood lights mounted on high poles. There was also a large amount of human traffic on the beach and vehicle traffic on the nearby roads.

The presence of unshielded lights directly visible from the beach is reflected in both the zenith and horizon SQM data, with the horizon values the lowest (and therefor the brightest) recorded during the entire survey. The zenith value, which represents the overhead sky glow value un affected by directly visible light sources, is representative of a locally bright night sky, similar to the sky over the Mooloolaba and Buddina sites monitoring sites, both exposed to bright unshielded parking lot lights.

*Coolum beach* – north. This, much darker location was located away from the public area of the beach and average magnitude describes a much darker nesting habitat. The results show an approximate decrease in zenith and horizon luminance values between Coolum South and Coolum north of 30% and 68% respectively.

# 5 CONCLUSION

The primary source of sky glow was towns and cities located along the regional coastline. An additional light source that may have contributed to sky glow from some locations was the Sunshine Coast Airport and the adjacent road works associated with the planned Airport Expansion project, which is scheduled for completion in 2018. Glow from Brisbane and the extended urban zone between Pelican Waters in the south and Mooloolaba in the north cumulatively, contributes to sky glow visible from beaches along the entire Sunshine Coast extending as far north as Coolum and to Woorim in the south (Moreton Bay).

The survey clearly demonstrated the effect clouds have on whole of sky illumination by scattering and reflecting light from multiple sources over a broad geographic area. This included light from sources that were remote or screened from the beach at ground level, yet strongly illuminated the entire sky above the nesting beach. The amplification of bright white LED lights by clouds was particularly notable, reducing sky quality by more than 500 %.

## 5.1 Recommendations

To improve the quality of nesting habitat on the Sunshine Coast and in the Moreton Bay Region, we make the following recommendations based on the findings of the 2017 Benchmark ALAN survey, not listed in any specific order:

1. Understand LED light emissions.

Additional more conclusive data, captured within a carefully designed controlled experiment, will provide a better understanding of the relative contribution of LED light emissions at monitoring sites where street and carpark lighting is located adjacent to the nesting beach.

2. Manage LED lighting fixtures.

The following management controls should be applied to all LED lighting. Ensure that LEDs:

- Have a 3000 K CCT limit;
- Contain as little blue wavelength light as possible;
- Are amber (and not white);
- Are at the minimum wattage required to protect public safety; and
- Are managed to reduce upward light spill and glare.

3. Design and manage all lighting fixture types.

Modification of poorly managed and inappropriately positioned lighting fixtures located adjacent to the nesting beach; typically carpark, street and public facility lighting. In general, each fixture should be either appropriately designed or modified as follows:

- Reduce height;
- Change the lamp type;
- Decrease the wattage;
- Add shielding to reduce outward glare;

- Orient lights away from the beach;
- Add motions sensors;
- Add timers to include a curfew time; and
- In all cases, the most cost-effective solution with the greatest impact on light reduction is to switch them off.

4. Modify lighting fixtures as per **Section 3.3**

Address the recommendations given in **Table 7** for modification of specific, problematic lighting fixtures including:

- Buddina, Point Cartwright: Toilet and carpark lights to be reduced (lowered, shielded), gazebo light to be fixed/removed/replaced.
- Mooloolaba: Fix the gazebo light and modify LED lights in carpark
- Shelly beach: [redacted] Modify all street lighting on William St visible from the nesting beach. Modify street lighting on the corner of William Street and Ocean Court.

5. Create dark horizon cues.

Maintenance of existing features that elevate the dark horizon and provide key ocean-finding cues for hatchlings and dark zones for adult nesting. Such features are dunes, cliff face, tall trees, potentially other, unlit man-made structures and vegetation screens.

6. Create new, or maintain existing, vegetation screening.

The importance of vegetation at the nesting beach cannot be over stated. Planting trees and vegetation and maintaining existing vegetation screens is critical to the maintenance of suitable nesting habitat. Trees shield the beach from light, supporting adult nesting and providing a tall, dark horizon cue against which hatchlings can orient themselves toward the ocean.

Vegetation will stabilize the dune profile, providing protection from predicted sea level rise and modified tidal systems. Regardless of whether existing lighting fixtures can be suitably modified, vegetation screening should be either put in place, or if existing, maintained, at all nesting habitat.

7. Consider orientation in building design.

The amount of light emitted into the sky is reduced when buildings are oriented away from the beach, avoiding direct light spill onto the nesting habitat.

8. Conduct another audit of lighting fixtures.

Follow modifications with an audit to determine effectiveness of management options and identify any remaining brightly lit areas and problematic fixtures that require additional modification.

9. Monitor hatchling orientation at the nesting beach

Systematic collection of data on hatchling sea-finding orientation immediately following emergence from the clutch will provide ongoing evidence of the effectiveness of all lighting management actions. Data should be gathered using the methodology developed by Pendoley (2005) and outlined in the relevant PENV Standard Operating Procedure to determine a. the range of dispersion and b. degree of deflection from the most direct route toward the ocean.

This approach, now standard nationwide, provides data that can be easily integrated with light profile data quantified using Sky42™ and the resulting data set and examined for statistically significant correlation between indices of orientation, artificial light and exiting topographical features. Information will be provided regarding areas that either need further attention or where lighting management has been successful.

10. Repeat this ALAN Survey.

As light profiles are continually changing, keeping pace with development and subject to nationwide initiatives such as the current LED movement, it is recommended that this ALAN survey is repeated whenever resources allow. Repeat surveys provide information to quantify the impact on brightness resulting from either implementation of the above recommendations or additional light emissions from human development in the region.

# 6 REFERENCES

AUBÉ, M., KOCIFAJ, M., ZAMORANO, J., LAMPHAR, H.S. & DE MIGUEL, A.S. (2016) The spectral amplification effect of clouds to the night sky radiance in Madrid. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *181*, pp.11-23.

AUSTRALIAN BUREAU OF STATISTICS (2011) Regional Population Growth, Australia. Table 3: Estimated Resident Population, Local Government Areas, Queensland Accessed online accessed 18/10/2017 at: http://www.abs.gov.au/ausstats/abs@.nsf/Latestproducts/3218.0Main%20Featuresnb752016?opendocument&tabname=Summary&prodno=3218.0&issue=2016&num=&view=].

BARÁ, S. (2017) Characterizing the zenithal night sky brightness in large territories: How many samples per square kilometre are needed? *arXiv preprint arXiv:1705.05788*.

BARTOL, S.M. & MUSICK, J. (2003) Sensory biology of sea turtles. In: Biology of Sea Turtles, Lutz P and Musick J (Eds) CRC Press, Boca Raton.

BERRY, M., BOOTH, D.T. & LIMPUS, C.J. (2013) Artificial lighting and disrupted sea-finding behaviour in hatchling loggerhead turtles (*Caretta caretta*) on the Woongarra coast, south-east Queensland, Australia. *Australian Journal of Zoology* **61**: 137-145.

CARR, A. & OGREN, L. (1960) The ecology and migrations of sea turtles. 4. The green turtle in the Caribbean Sea. *Bulletin of the American Museum of Natural History* **121**: 7-48.

CRAWFORD, B.H. (1949) The scotopic visibility function. *Proceedings of the Physical Society, Section B*, **62**, 321 – 334.

FALCHI, F. (2011) Campaign of sky brightness and extinction measurements using a portable CCD camera. Monthly notices of the Royal Astronomical Society 412.1 (2011): 33-48.

FALCHI, F., CINZANO, P., DURISCOE, D., KYBA, C.C., ELVIDGE, C.D., BAUGH, K., PORTNOV, B.A., RYBNIKOVA, N.A. & FURGONI, R. (2016) The new world atlas of artificial night sky brightness. *Science advances*, *2*(6), p.e1600377.

GASTON, K.J., VISSER, M.E. & HÖLKER, F. (2015). The biological impacts of artificial light at night: the research challenge. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, ***370*** (1667), 20140133.

GRECH, A., BOS, M., BRODIE, J., COLES, R., DALE, A., GILBERT, R., HAMANN, M., MARSH, H., NEIL, K. & PRESSEY, R. (2013) Guiding principles for the improved governance of port and shipping impacts in the Great Barrier Reef. *Marine Pollution Bulletin* **75**: 8-20.

GYURIS, E. (1993) Factors that control the emergence of green turtle hatchlings from the nest. *Wildlife Research* **20**: 345-353.

HODGE, W., LIMPUS, C.J. & SMISSEN, P. (2007) Queensland turtle conservation project: Hummock Hill Island nesting turtle study December 2006. Environmental Protection Agency, Queensland, Australia.

JECHOW, A., KOLLÁTH, Z., RIBAS, S.J., SPOELSTRA, H., HÖLKER, F. & KYBA, C. (2017) Imaging and mapping the impact of clouds on skyglow with all-sky photometry. arXiv preprint arXiv:1705.04968.

KAMROWSKI, R.L. (2014) Coastal light pollution in Australia: insights and implications for marine turtle conservation. PhD Thesis, James Cook University, Townsville, Queensland.

KAMROWSKI, R.L., LIMPUS, C., JONES, R., ANDERSON, S. & HAMANN, M. (2014a) Temporal changes in artificial light exposure of marine turtle nesting areas. *Global Change Biology* **20**: 2437-2449.

KAMROWSKI, R.L., LIMPUS, C., MOLONEY, J. & HAMANN, M. (2012) Coastal light pollution and marine turtles: assessing the magnitude of the problem. *Endangered Species Research* **19**: 85-98.

KAMROWSKI, R.L., LIMPUS, C., PENDOLEY, K.L. & HAMANN, M. (2014b) Influence of industrial light pollution on the sea-finding behaviour of flatback turtle hatchlings. *Wildlife Research* **41**: 421 – 434.

KOCH, A.U., GUINEA, M.L. & WHITING, S.D. (2008) Asynchronous emergence of Flatback sea turtles, *Natator depressus*, from a beach hatchery in Northern Australia. *Journal of Herpetology* **42**: 1-8.

KOLLÁTH, Z., 2010. Measuring and modelling light pollution at the Zselic Starry Sky Park. In *Journal of Physics: Conference Series* (Vol. 218, No. 1, p. 012001). IOP Publishing.

KYBA, C., RUHTZ, T., FISCHER J., & HOLKER, F. (2012) Red is the new black: how the colour of urban skyglow varies with cloud cover. *Monthly Notices of the Royal Astronomical Society*, **425**, 701 – 708.

KYBA, C.C., RUHTZ, T., FISCHER, J. & HÖLKER, F. (2011) Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems. *PloS one*, *6*(3), p.e17307.

LIMPUS, C.J. (1971). Sea turtle ocean finding behaviour. - Search 2, p. 385-387. (1982). The status of Australian sea turtle populations. In: *Biology and conservation of sea turtles* (K. A. BJOURNDAL, ed.). Smithsonian Institution Press, Washington, D. C.

LIMPUS, C. (1985) A study of the loggerhead turtle, *Caretta caretta*, in Queensland. Ph.D. University of Queensland, Brisbane.

LIMPUS, C. (2009) A biological review of Australian marine turtles. Environmental Protection Agency, Queensland Government, The State of Queensland.

LIMPUS, C.J. & KAMROWSKI, R.L. (2013) Ocean-finding in marine turtles: the importance of low horizon elevation as an orientation cue. *Behaviour* **150**: 863-893.

LIMPUS, C.J. & LIMPUS, D. (2003) Loggerhead turtles in the equatorial and southern Pacific Ocean: a species in decline. Loggerhead sea turtles. 2003:199-209.

LOHMANN, K.J., WITHERINGTON, B., LOHMANN, C.M.F. & SALMON, M. (1997) Orientation, navigation, and natal beach homing in sea turtles.*in* P. L. Lutz and J. A. Musick, editors. The biology of sea turtles. CRC Press, Boca Raton, FL.

MROSOVSKY, N. (1968) Nocturnal emergence of sea turtles: control by thermal inhibition of activity. *Nature* **220**: 1338-1339.

MROSOVSKY, N. & SHETTLEWORTH, S.J. (1968) Wavelength preferences and brightness cues in the water finding behaviour of sea turtles. *Behaviour* **32**: 211-257.

PENDOLEY, K. (2005) Sea turtles and the environmental management of industrial activities in north west Western Australia. Murdoch University, Perth, Western Australia.

PENDOLEY, K.L. & KAMROWSKI, R.L. (2015) Influence of horizon elevation on the sea-finding behaviour of hatchling flatback turtles exposed to artificial light-glow. *Marine Ecology Progress Series*.

RABAZA, O., GALADÍ-ENRÍQUEZ, D., ESTRELLA, A.E. & DOLS, F.A. (2010) All-sky brightness monitoring of light pollution with astronomical methods. *Journal of environmental management*, *91*(6), pp.1278-1287.

SALMON, M. (2003) Artificial night lighting and sea turtles. *Biologist* **50**: 163-168.

SALMON, M. & WITHERINGTON, B. (1995) Artificial lighting and seafinding by loggerhead hatchlings: Evidence for lunar modulation. *Copeia* **1995**: 931-938.

SALMON, M., REINERS, R., LAVIN, C., & WYNEKEN, J. (1995). Behavior of Loggerhead Sea Turtles on an Urban Beach. I. Correlates of Nest Placement. *Journal of Herpetology,29*(4), 560-567. doi:10.2307/1564739

SALMON, M., WITHERINGTON, B.E. & ELVIDGE, C.D. (2000) Artificial lighting and the recovery of sea turtles. Pages 25-34 *in* N. Pilcher and G. Ismail, editors. Sea turtles of the Indo-Pacific: Research, management and conservation. ASEAN Academic Press, London.

SALMON, M., WYNEKEN, J., FRITZ, E. & LUCAS, M. (1992) Seafinding by hatchling sea turtles: role of brightness, silhouette and beach slope as orientation cues. *Behaviour* **122**: 56-77.

SMITH, F. (1979) Reports on astronomy. *IAU Trans., XVIIA*: 218-222.

STARE, J. (2017) www.lightpolltuionmap.info VIIRS/DMSP and Earth Observatory Group NOAA National Geophysical Dta Centre https://ngdc.noaa.gov/eog/.

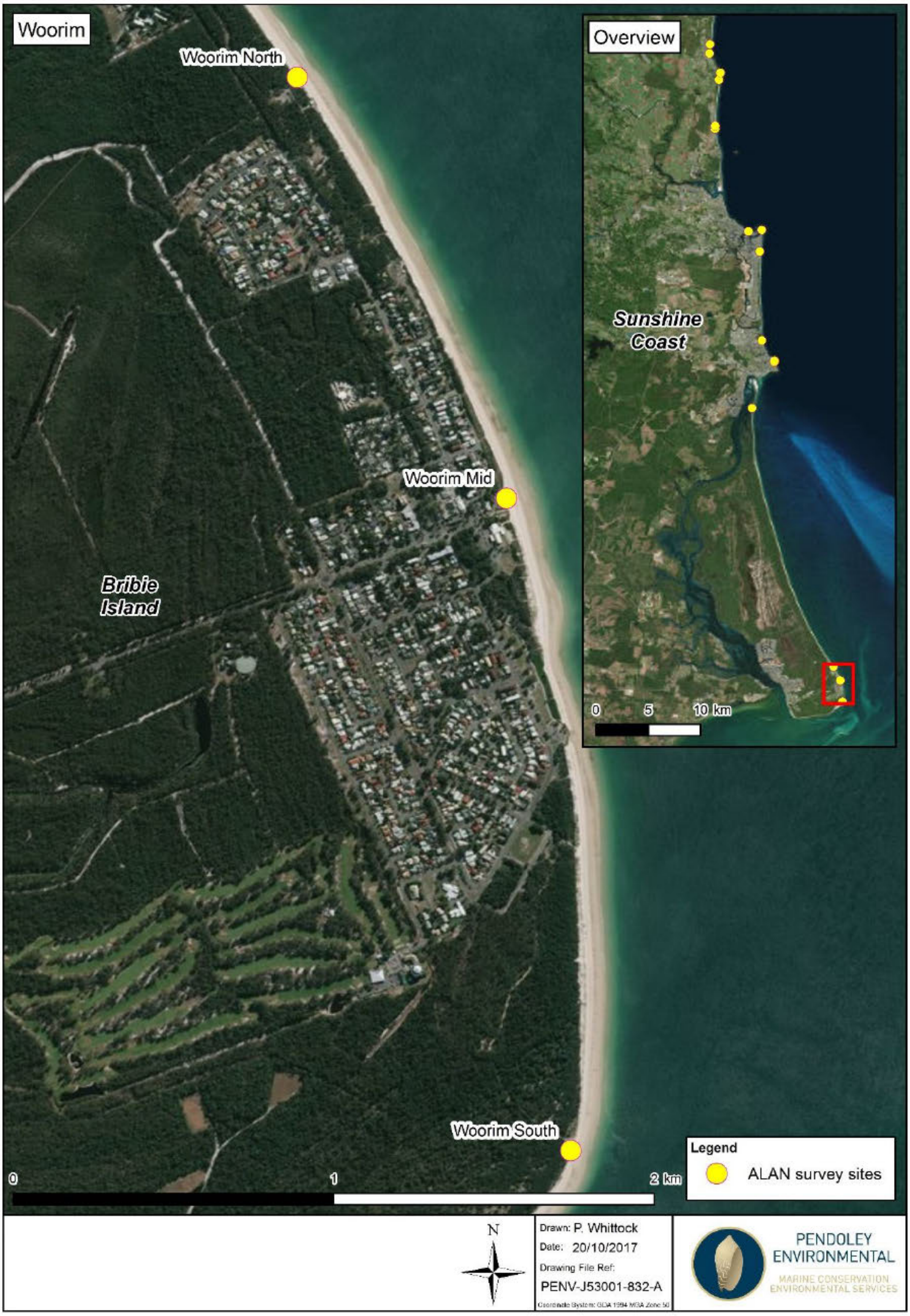
TALBERT, O.R., Jr., STANCYK, S.E., DEAN, J.M. & WILL, J.M. (1980) Nesting activity of the loggerhead turtle (*Caretta caretta*) in South Carolina I: a rookery in transition. *Copeia*: 709-719.

TUXBURY, S.M. & SALMON, M. (2005) Competitive interactions between artificial lighting and natural cues during seafinding by hatchling marine turtles. *Biological Conservation* **121**: 311-316.

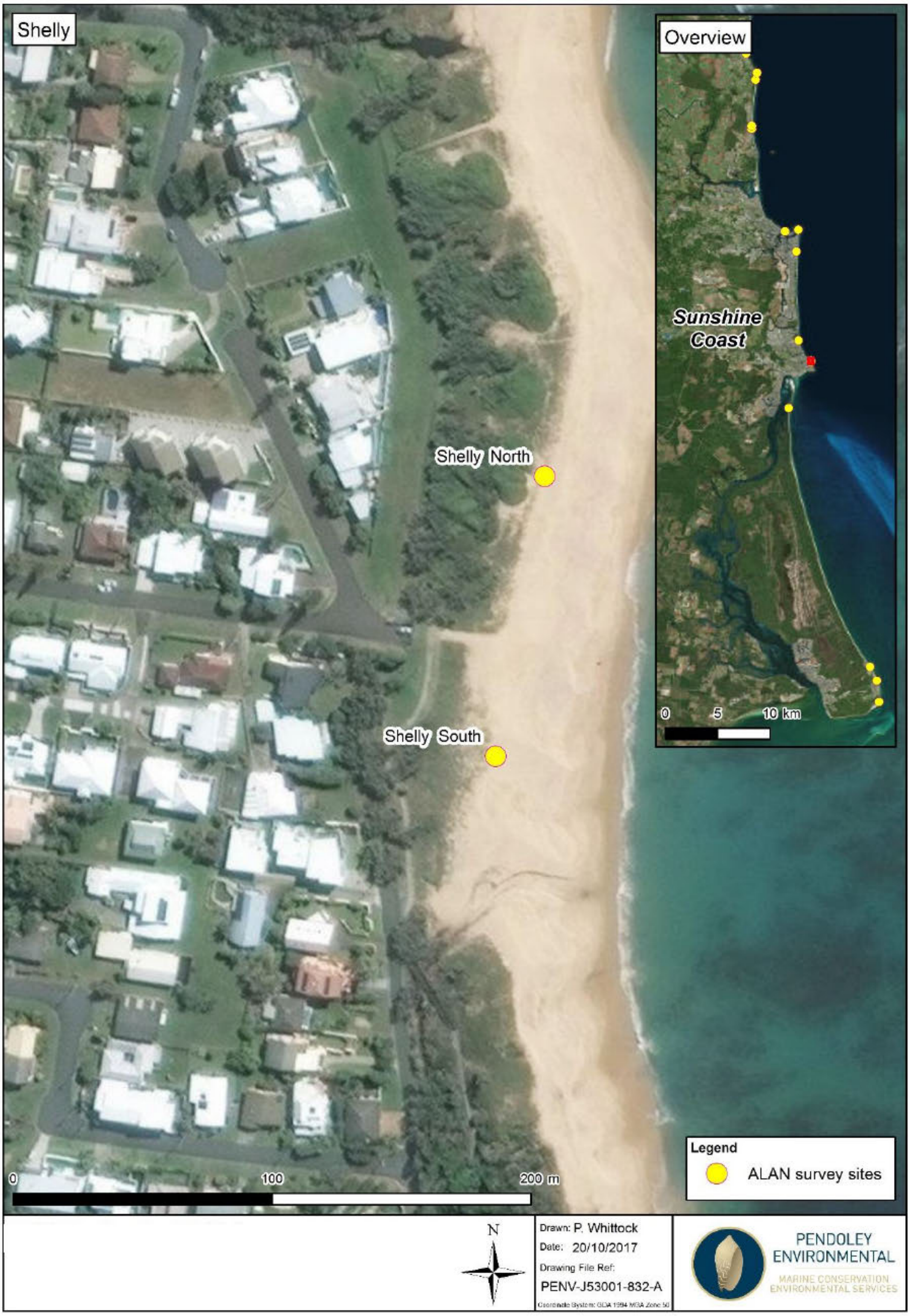
WITHERINGTON, B. & MARTIN, R.E. (2000) Understanding, assessing, and resolving light-pollution problems on sea turtle nesting beaches. 2nd ed., rev., Florida Fish and Wildlife Conservation Commission, Marine Research Institute, Tech. Rep. TR-2., St. Petersburg, FL.

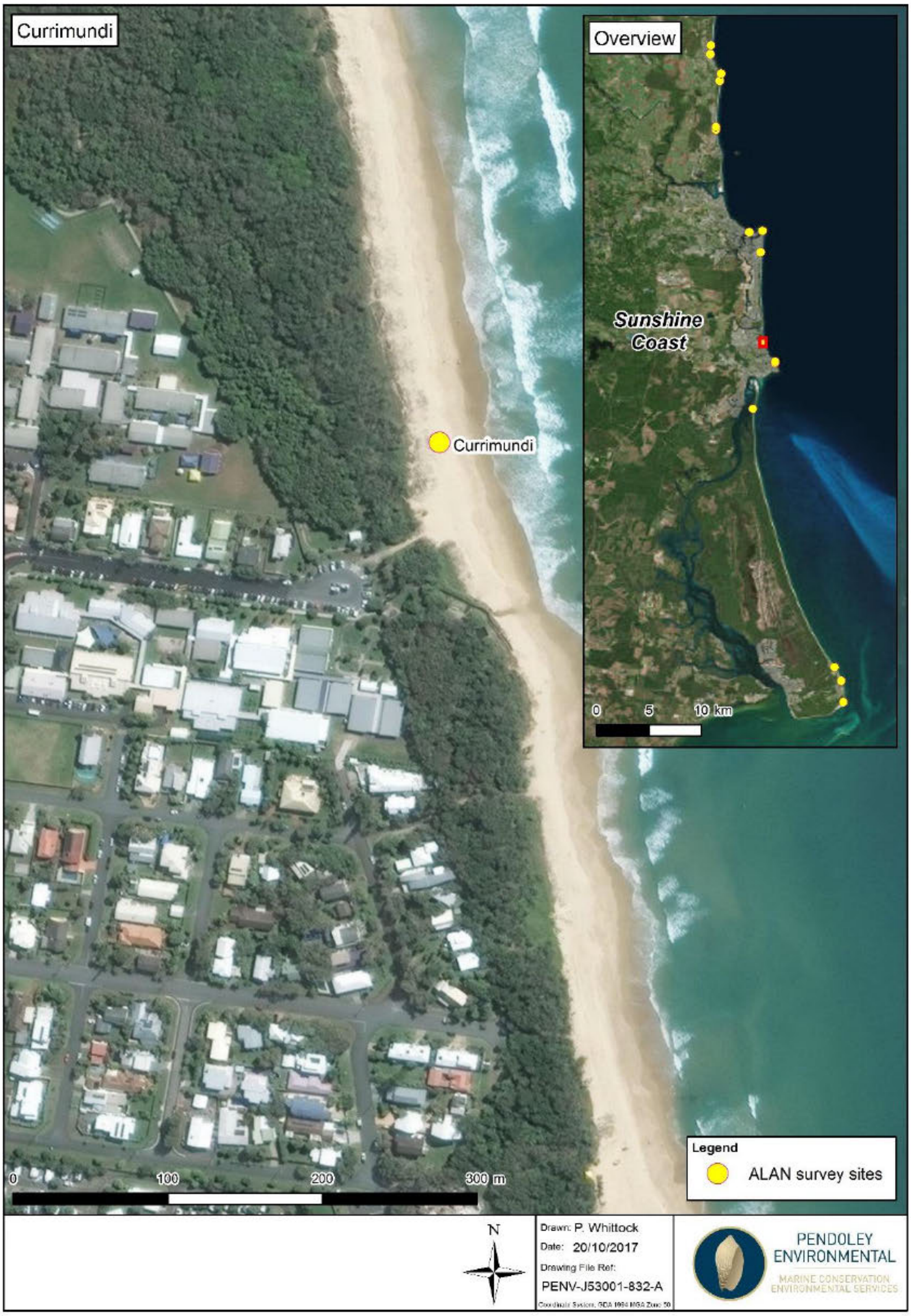
ZOTTI, G. (2007) October. Measuring light pollution with a calibrated high dynamic range all-sky image acquisition system. In*DARKSKY2007—7th European Symposium for the Protection of the Night Sky, Bled, Slovenia*.

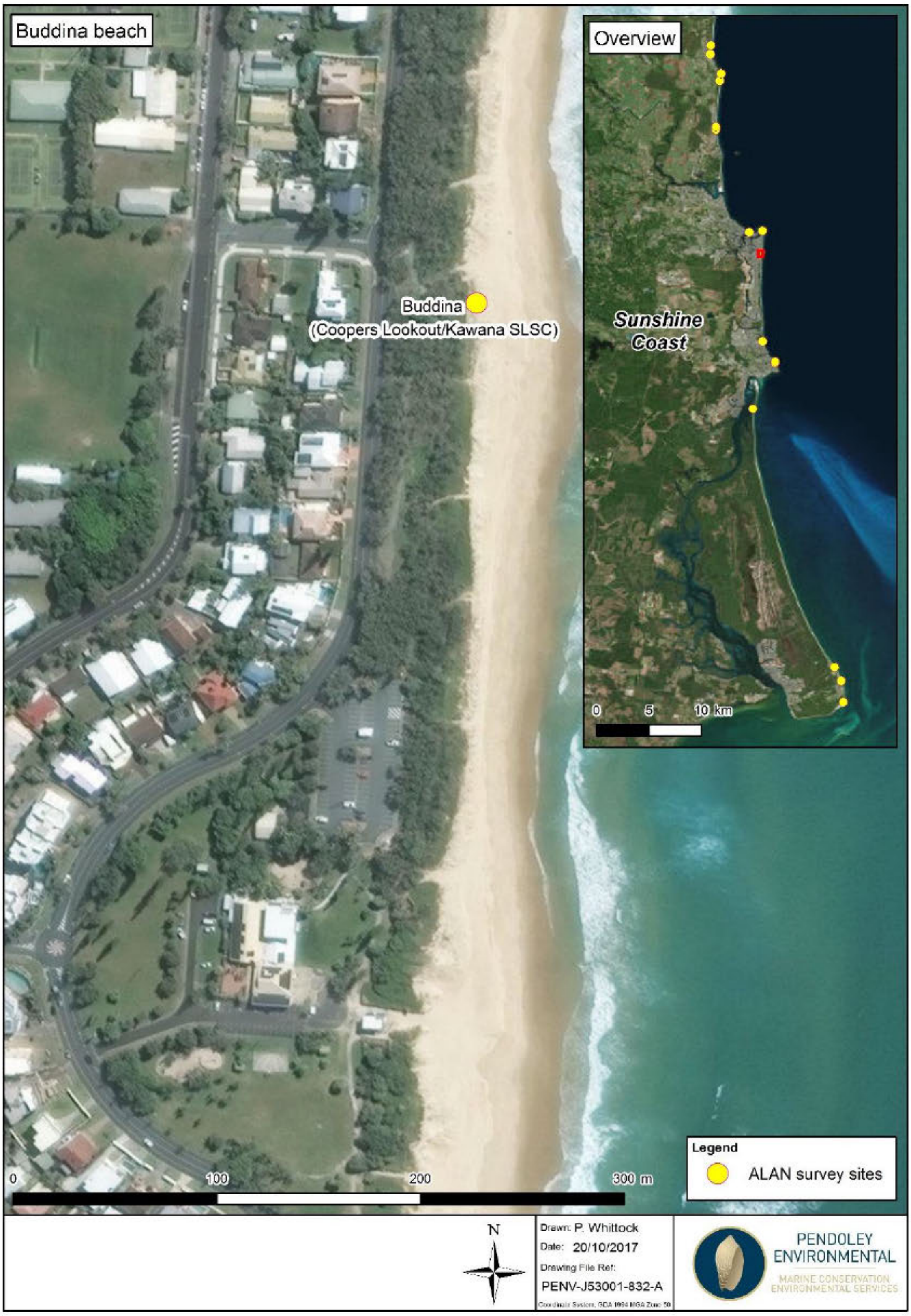
# APPENDIX A: MAPS SHOWING SKY42™ DEPLOYMENT LOCATIONS


Woorim
Woorim North
Woorim Mid
Woorim South
Bribie Island
Overview
Sunshine Coast
0 5 10 km
0 1 2 km
Legend
ALAN survey sites
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
Coordinate System: GDA 1994 MGA Zone 56
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES

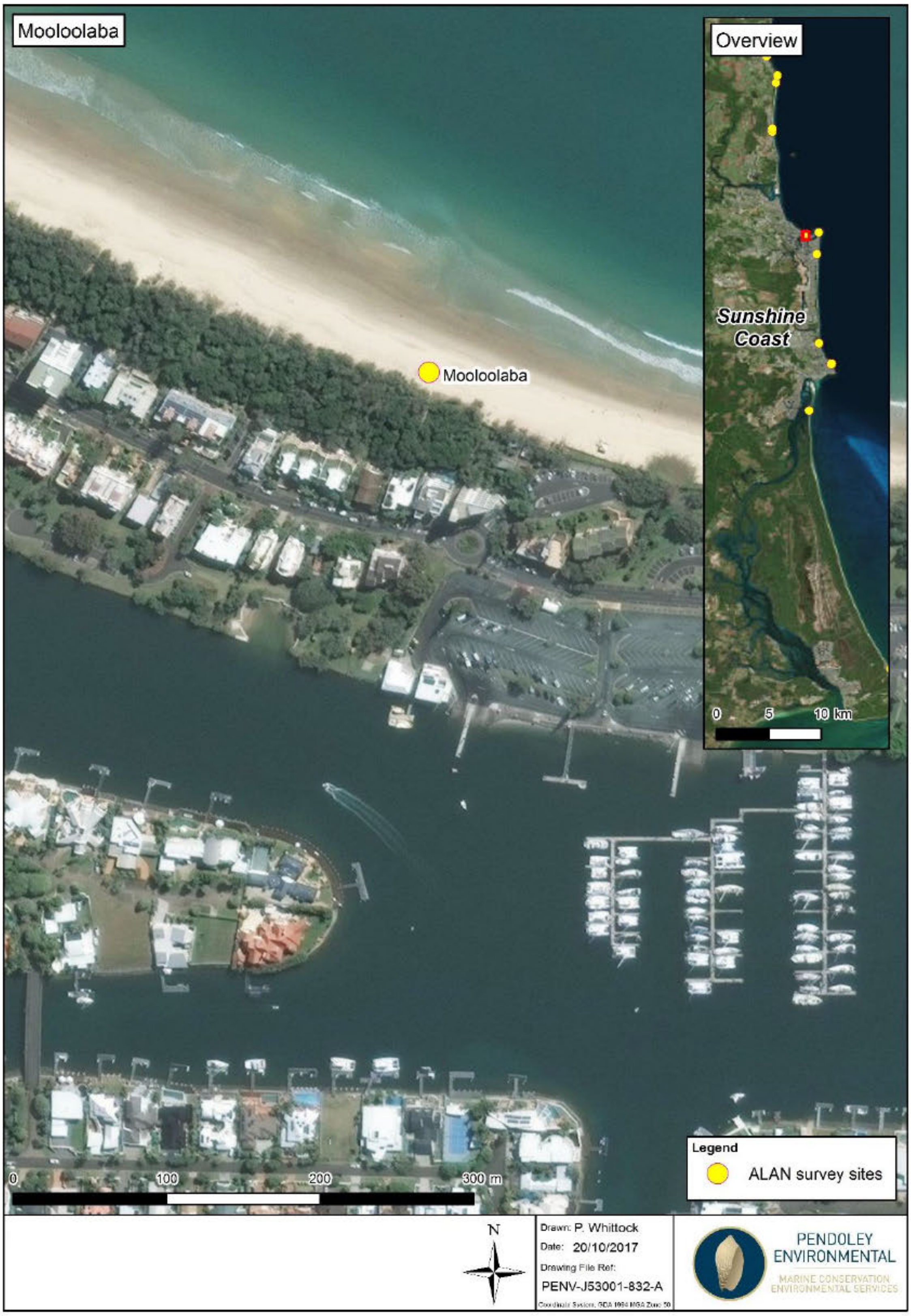

North Bribie Island
North Bribie Is.
0
500
1,000 m
Legend
ALAN survey sites
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION
ENVIRONMENTAL SERVICES

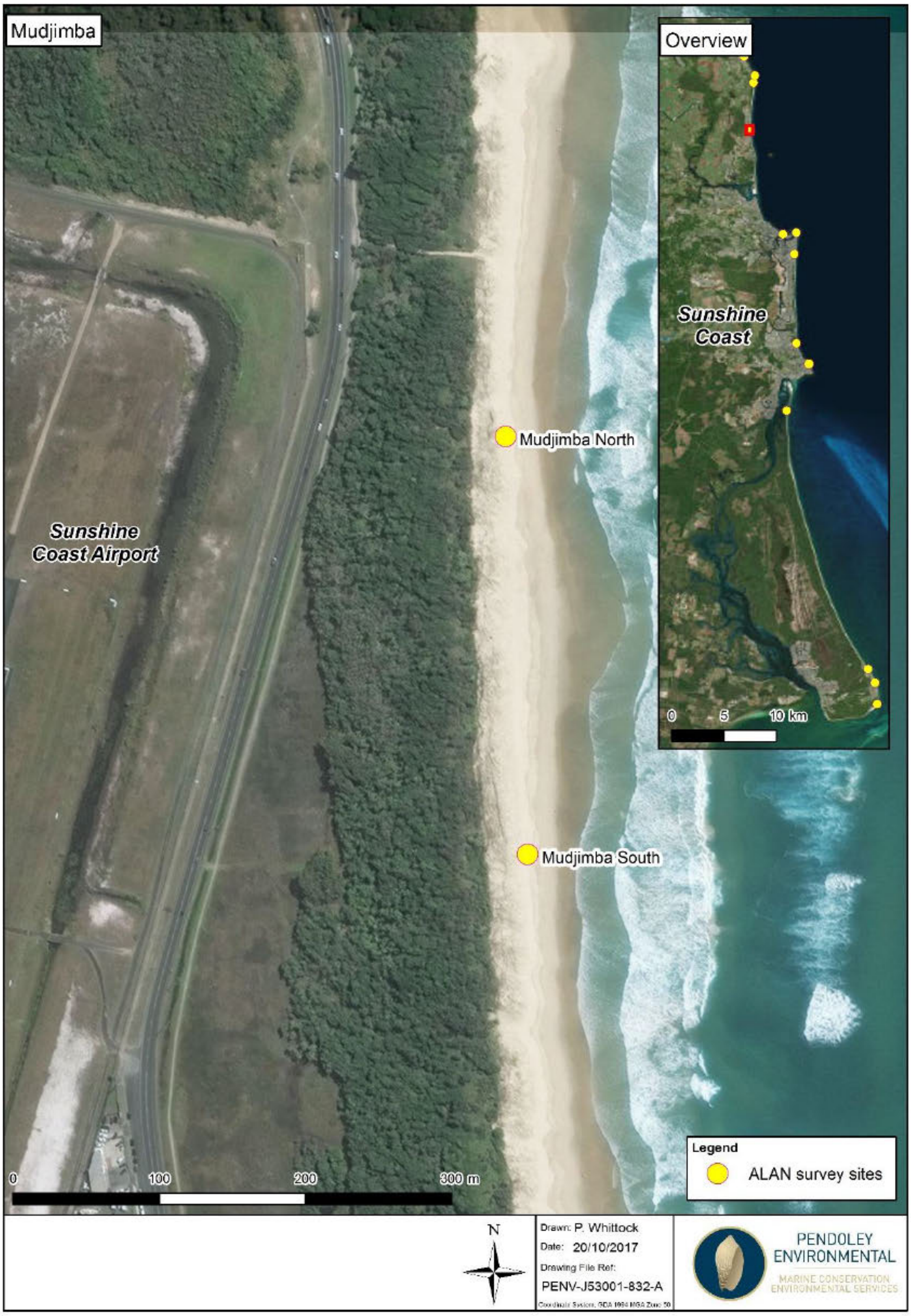

Shelly
Overview
Sunshine Coast
0
5
10 km
Shelly North
Shelly South
0
100
200 m
Legend
ALAN survey sites
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION
ENVIRONMENTAL SERVICES


Currimundi
Overview
Sunshine Coast
0 5 10 km
Currimundi
0 100 200 300 m
Legend
ALAN survey sites
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES

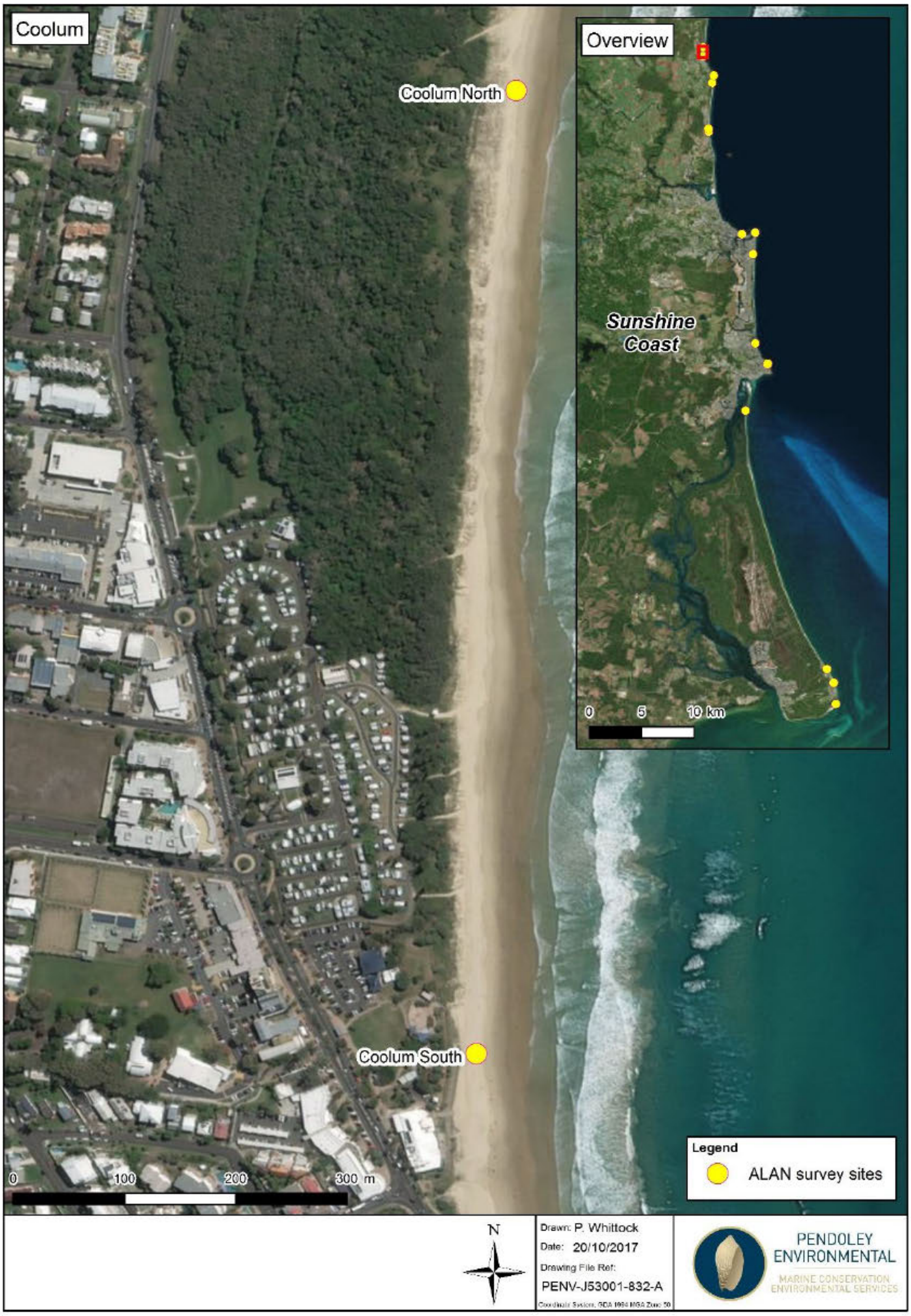

Buddina beach
Buddina
(Coopers Lookout/Kawana SLSC)
Overview
Sunshine Coast
0 5 10 km
0 100 200 300 m
Legend
ALAN survey sites
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES


Buddina
Overview
Sunshine Coast
0 5 10 km
Buddina Pt. Cartwright
Legend
ALAN survey sites
0 100 200 300 m
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES


Mooloolaba
Overview
Sunshine Coast
0 5 10 km
Mooloolaba
Legend
ALAN survey sites
0 100 200 300 m
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES


Mudjimba
Overview
Sunshine Coast
0 5 10 km
Mudjimba North
Mudjimba South
Sunshine Coast Airport
0 100 200 300 m
Legend
ALAN survey sites
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES


Yaroomba
Yaroomba North
Yaroomba South
Overview
Sunshine Coast
0 5 10 km
Legend
ALAN survey sites
0 100 200 m
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES


Coolum
Coolum North
Coolum South
Overview
Sunshine Coast
0 5 10 km
0 100 200 300 m
Legend
ALAN survey sites
N
Drawn: P. Whittock
Date: 20/10/2017
Drawing File Ref:
PENV-J53001-832-A
PENDOLEY ENVIRONMENTAL
MARINE CONSERVATION ENVIRONMENTAL SERVICES

## APPENDIX B: RAW SKY42™ IMAGES

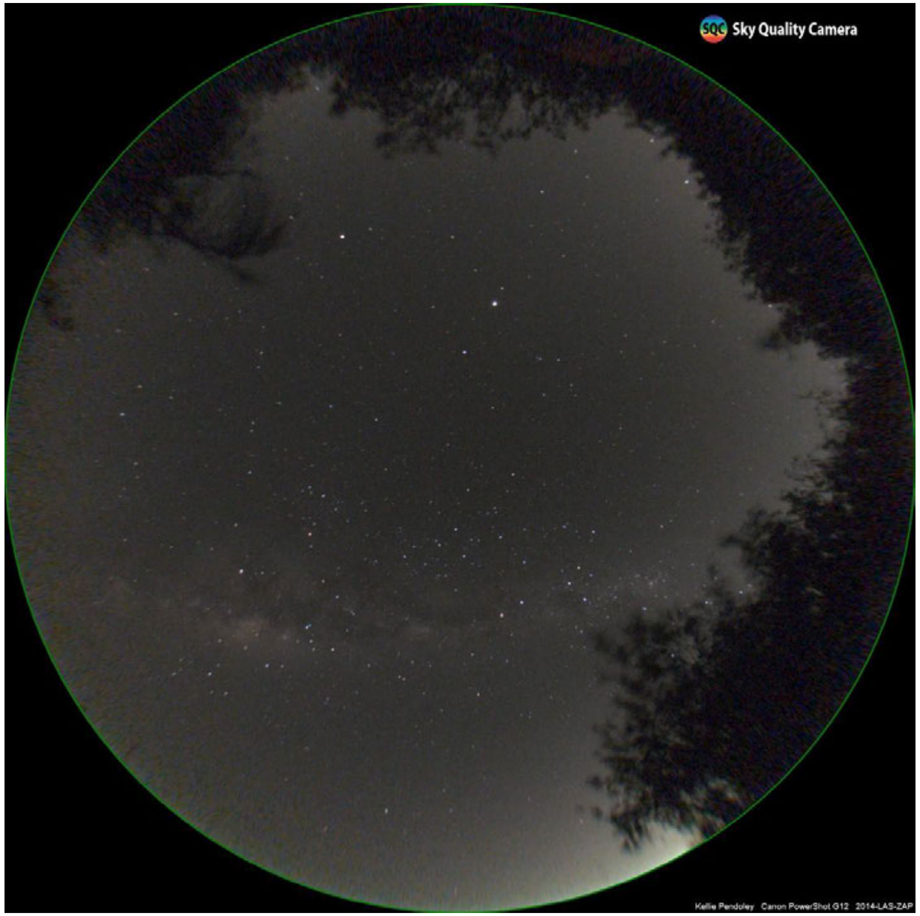



**Figure A1. Sky42 photograph of South Bribie (South), taken on 22nd June 2017.**

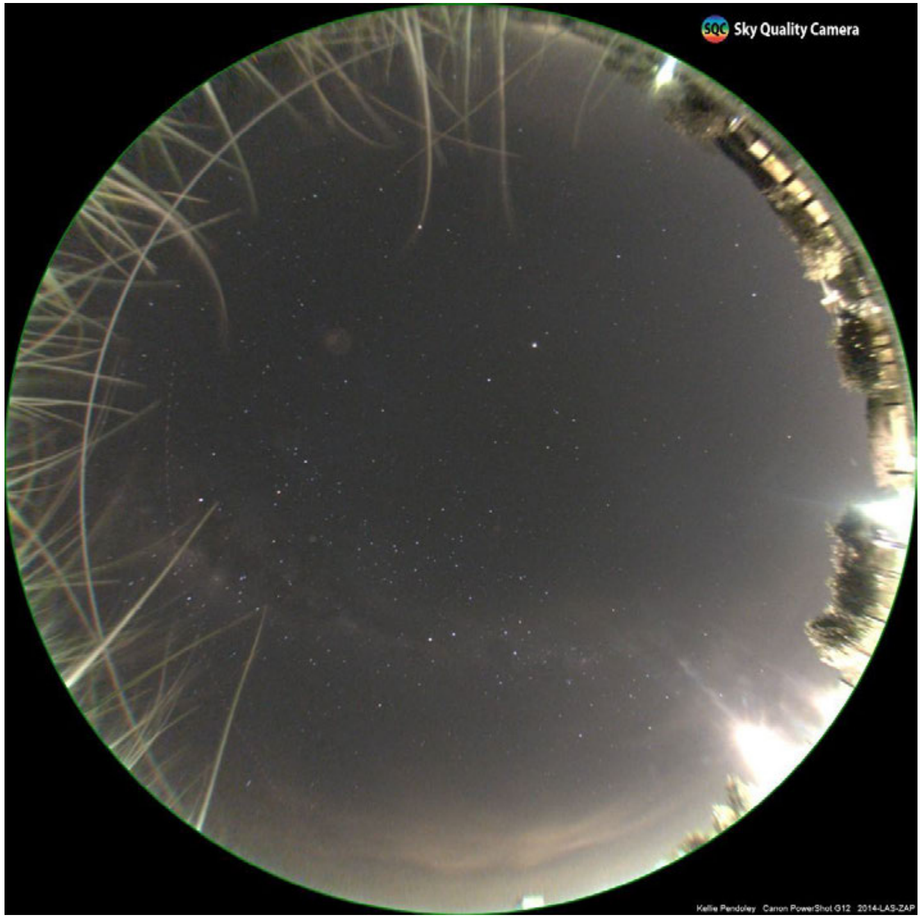



**Figure A2. Sky42 photograph of South Bribie (Mid), taken on 23rd June 2017.**

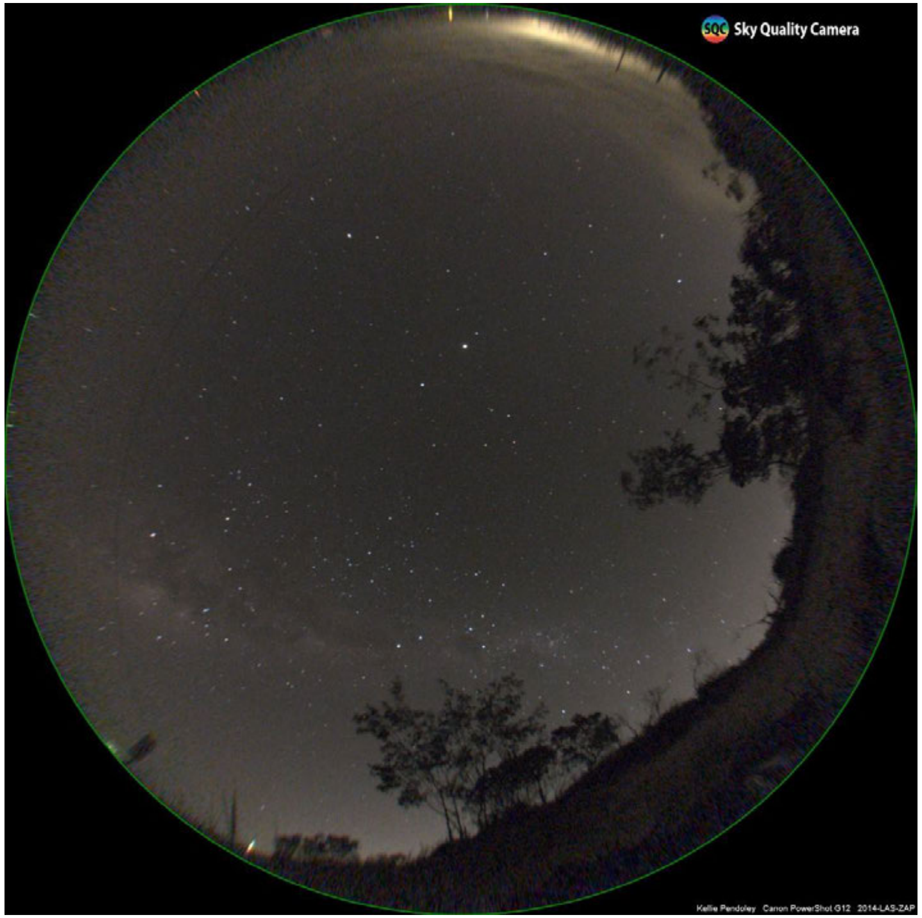



**Figure A3. Sky42 photograph of South Bribie (North), taken on 22nd June 2017.**

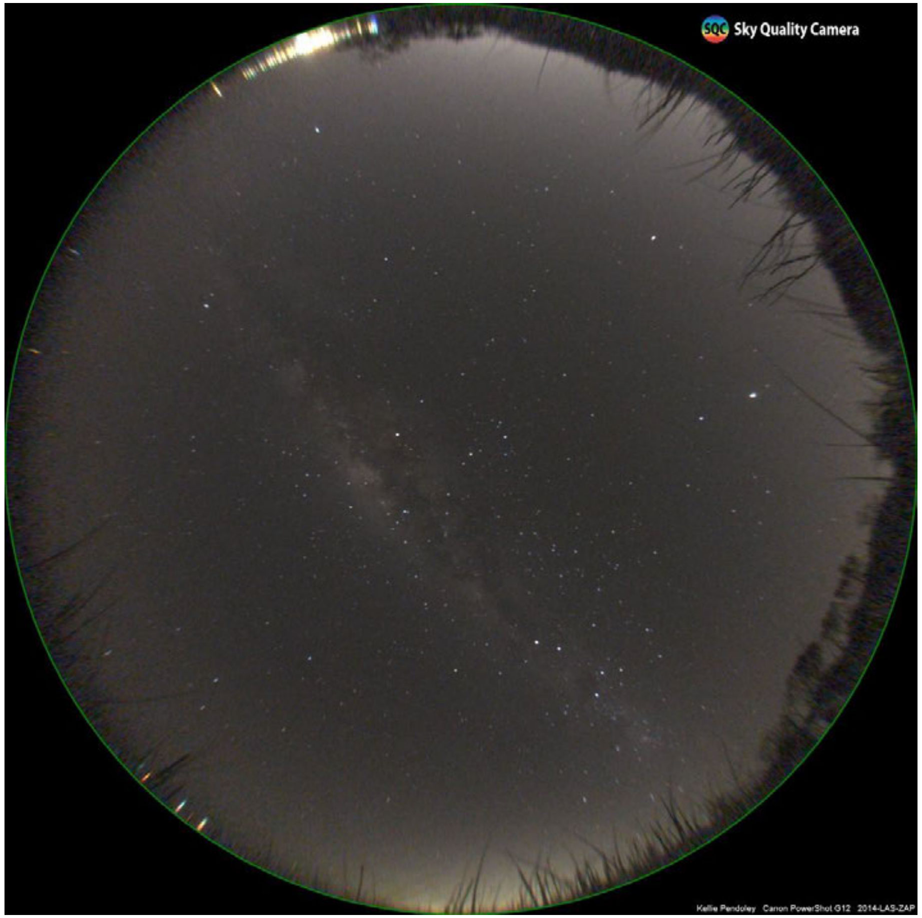



**Figure A4. Sky42 photograph of North Bribie, taken on 22nd June 2017.**

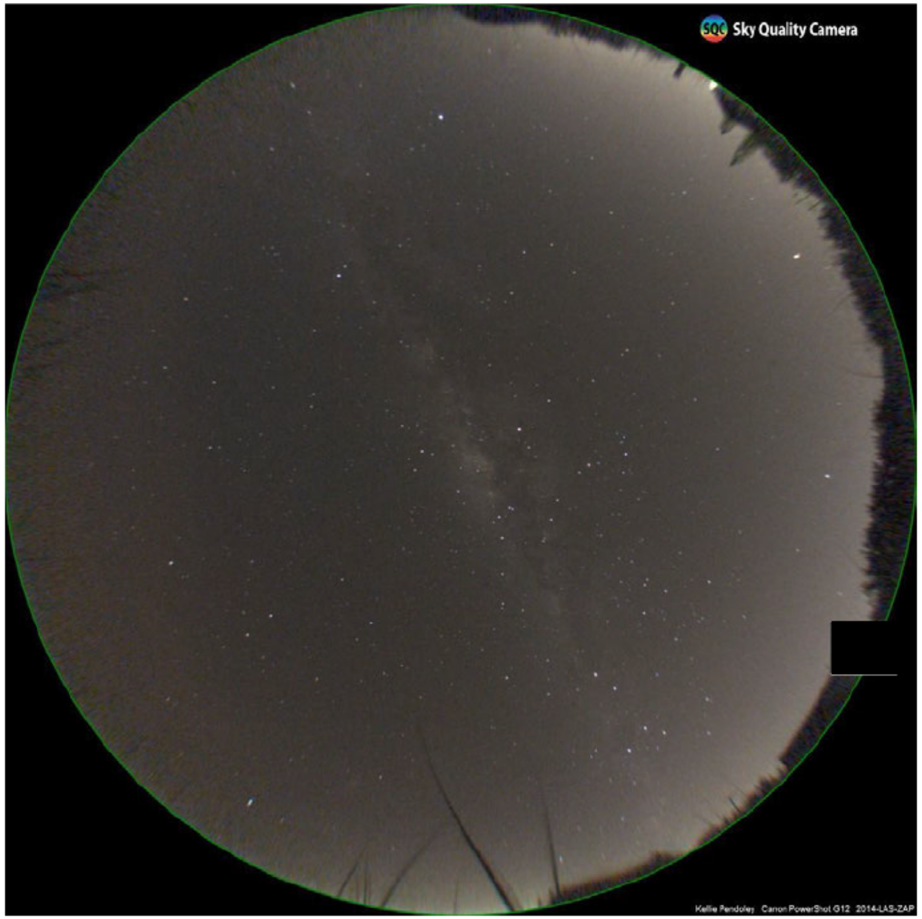



**Figure A5. Sky42 photograph of Shelly Beach (South), in clear conditions [redacted] Taken on 24th June 2017.**

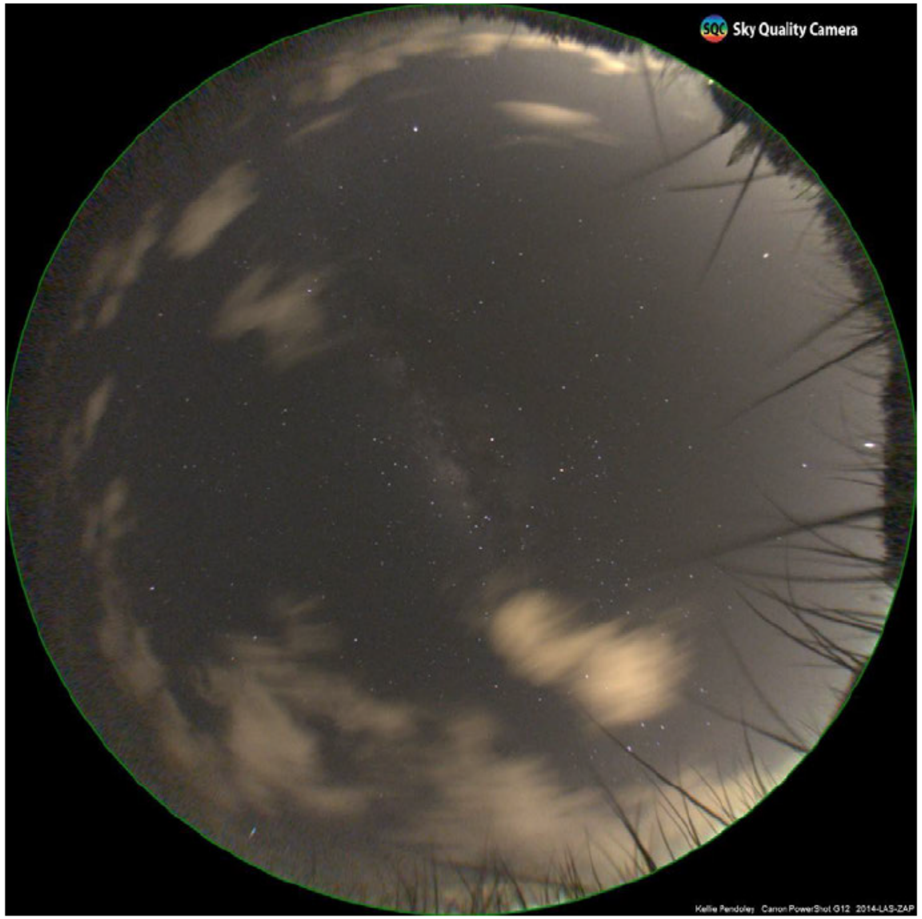



**Figure A6. Sky42 photograph of Shelly Beach (South) in cloudy conditions. Taken on 26th June 2017.**

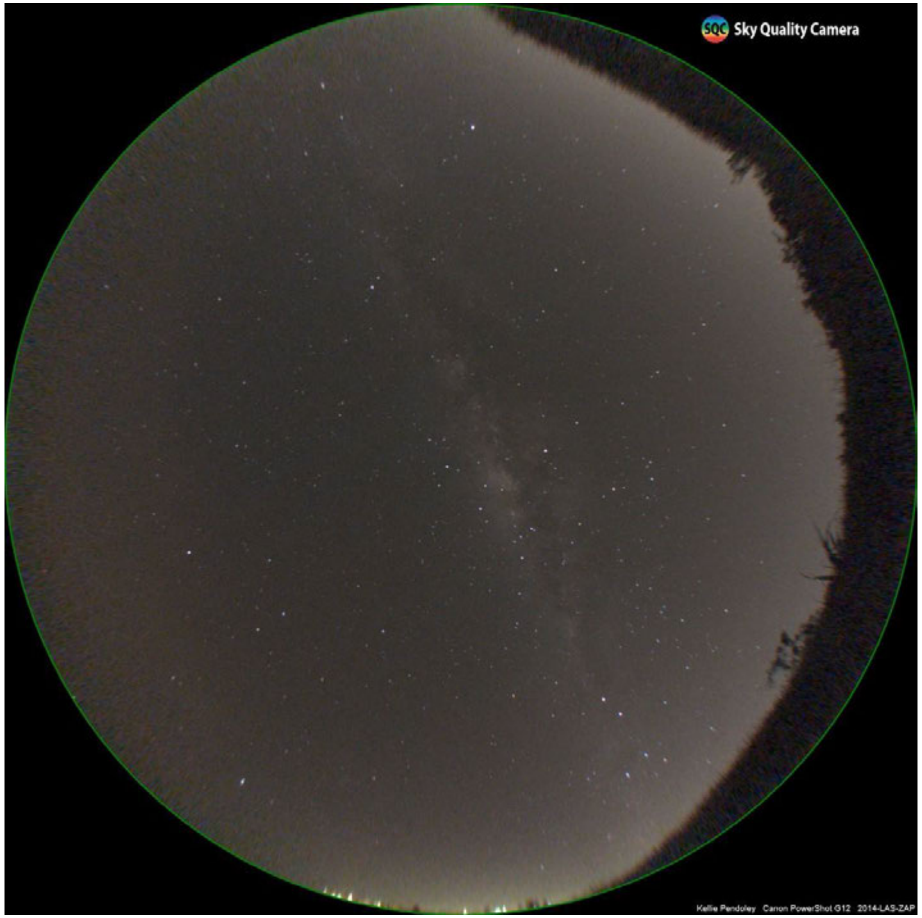



**Figure A7. Sky42 photograph of Shelly Beach (North), in clear conditions. Taken on 24th June 2017.**

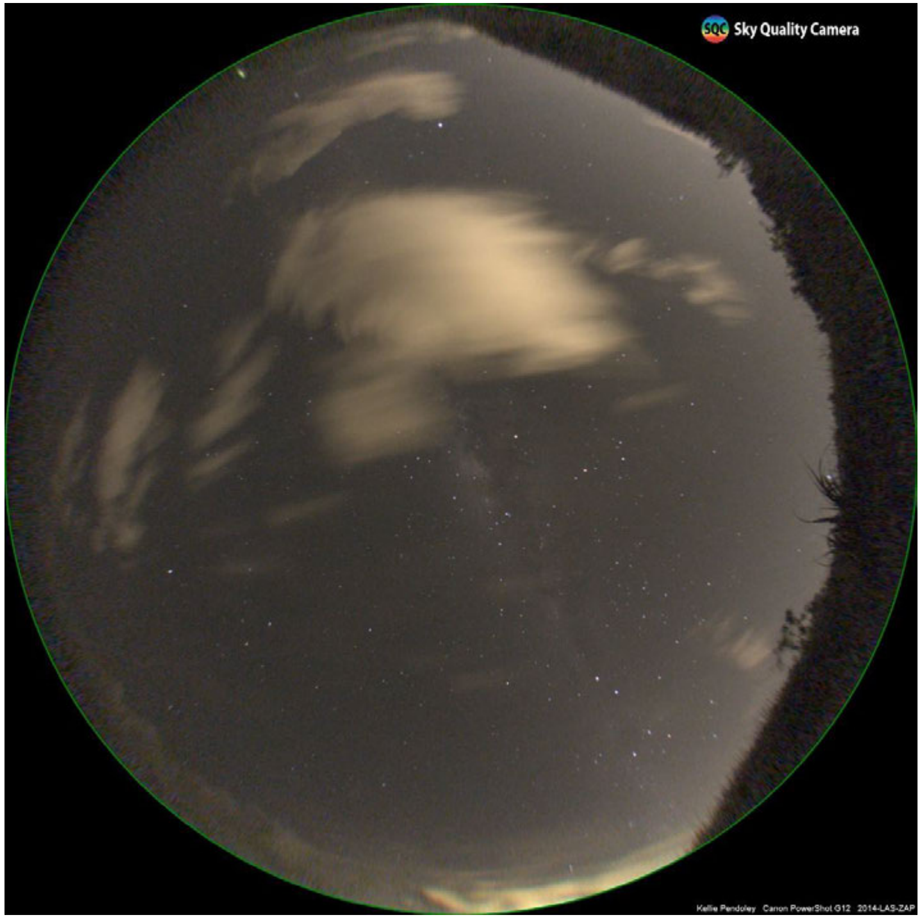



**Figure A8. Sky42 photograph of Shelly Beach (North), in cloudy conditions. Taken on 26th June 2017.**


**Figure A9. Sky42 photograph of Currimundi, in clear conditions. Taken on 24th June 2017.**

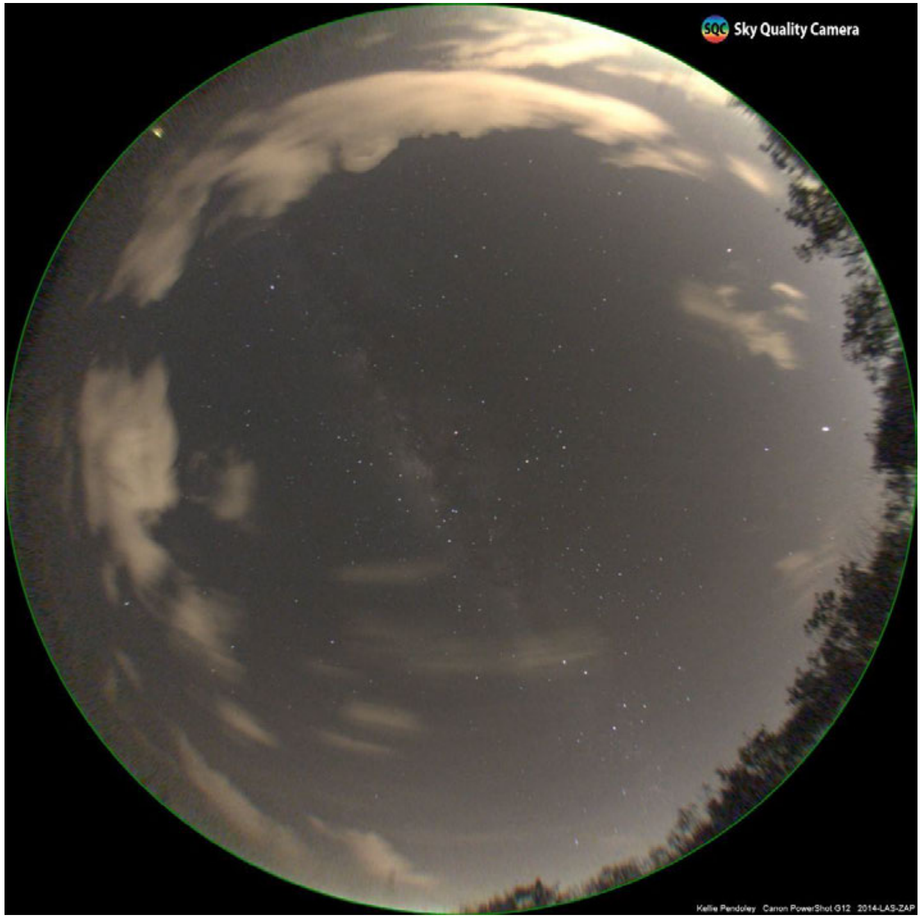



**Figure A10. Sky42 photograph of Currimundi, in cloudy conditions. Taken on 26th June 2017.**

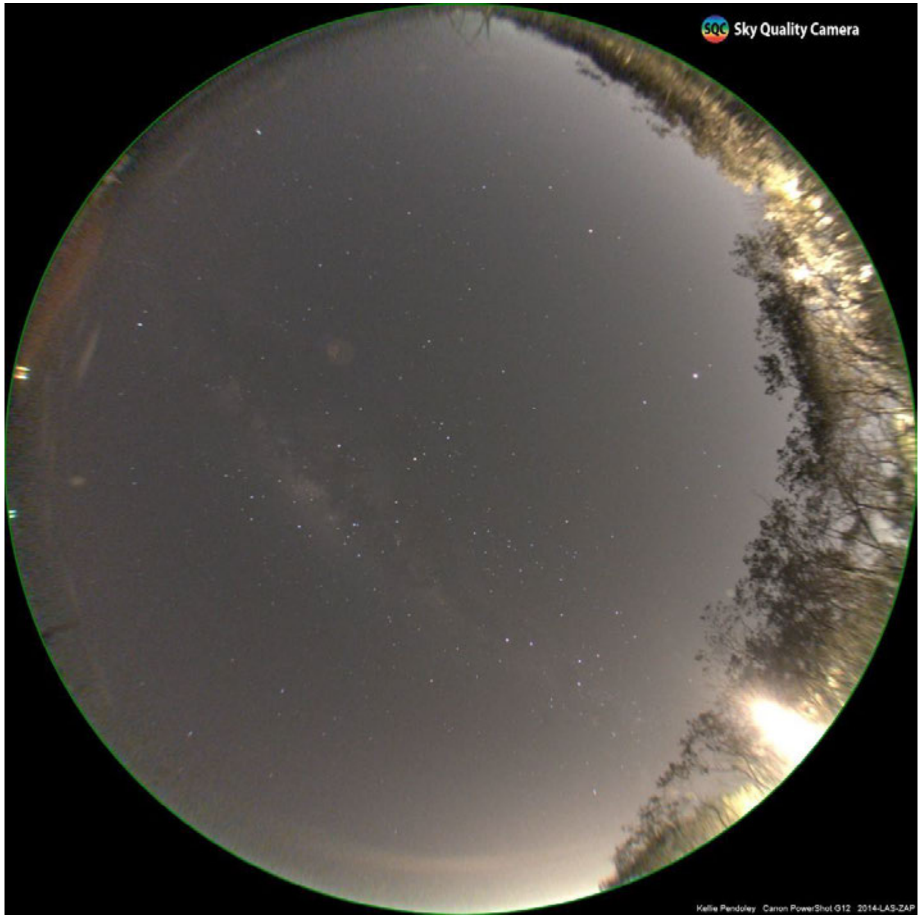



**Figure A11. Sky42 photograph of Buddina (Cooper's Lookout) with all carpark lights on (Scenario A). Taken on 25th June 2017.**

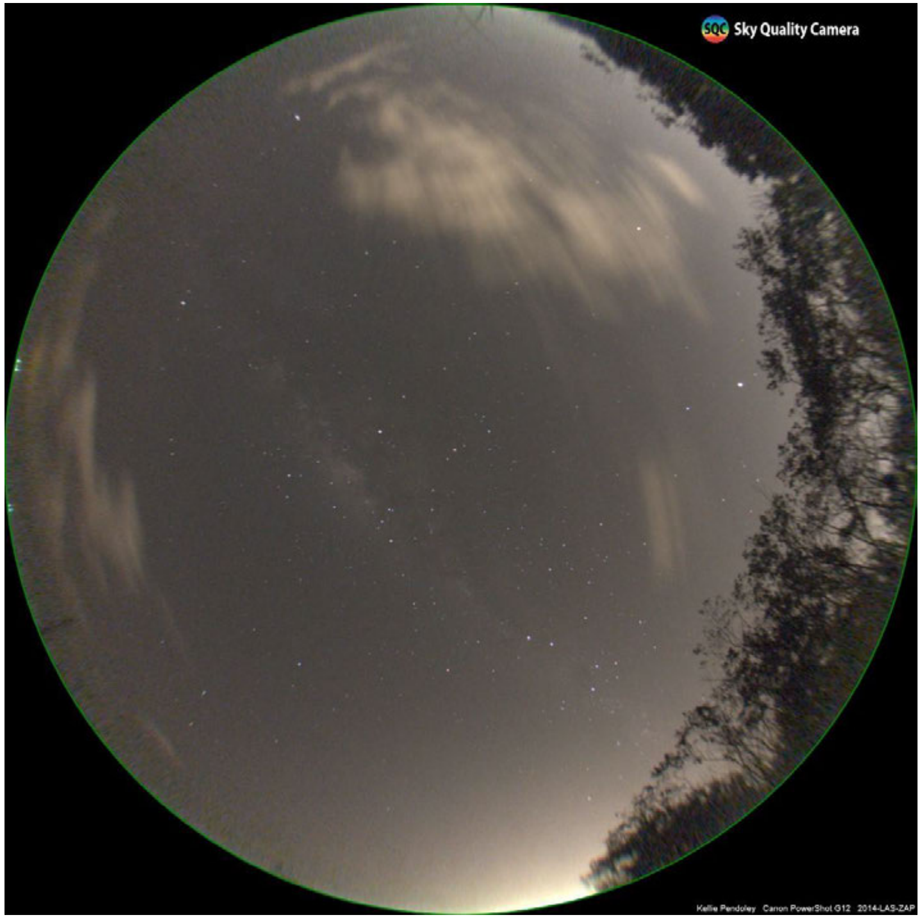



**Figure A12. Sky42 photograph of Buddina (Cooper's Lookout) with all carpark lights off (Scenario B). Taken on 25th June 2017.**

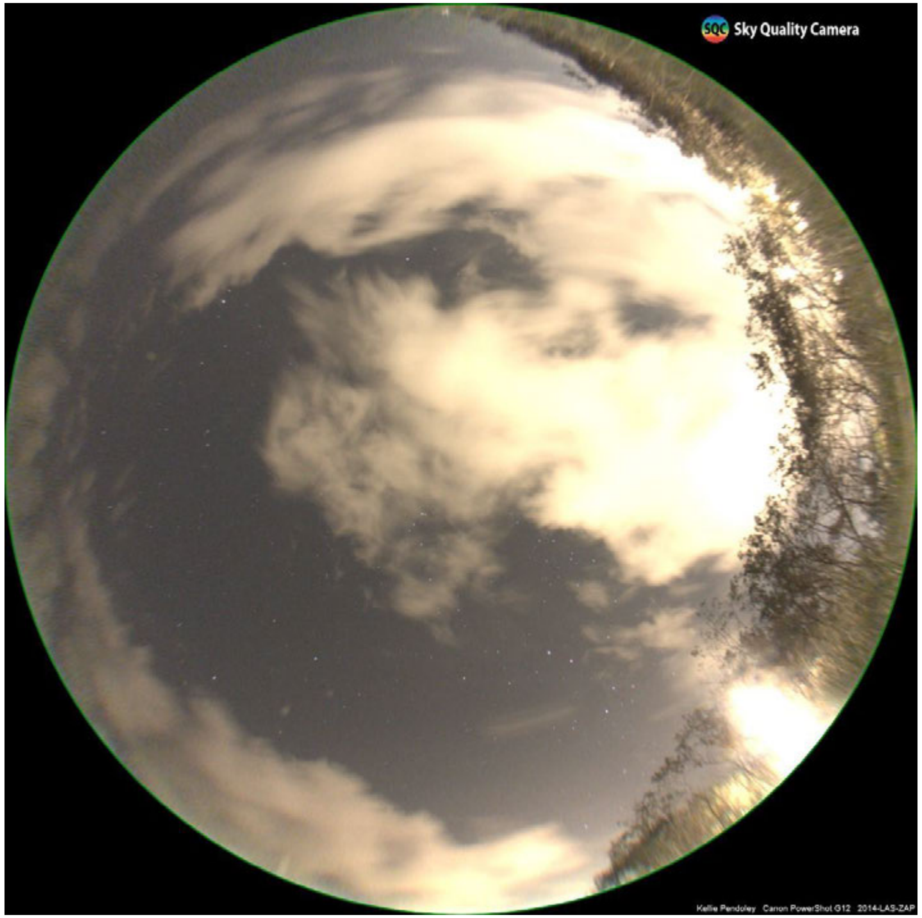



**Figure A13. Sky42 photograph of Buddina (Cooper's Lookout) with carpark lights on in cloudy conditions. Taken on 26h June 2017.**

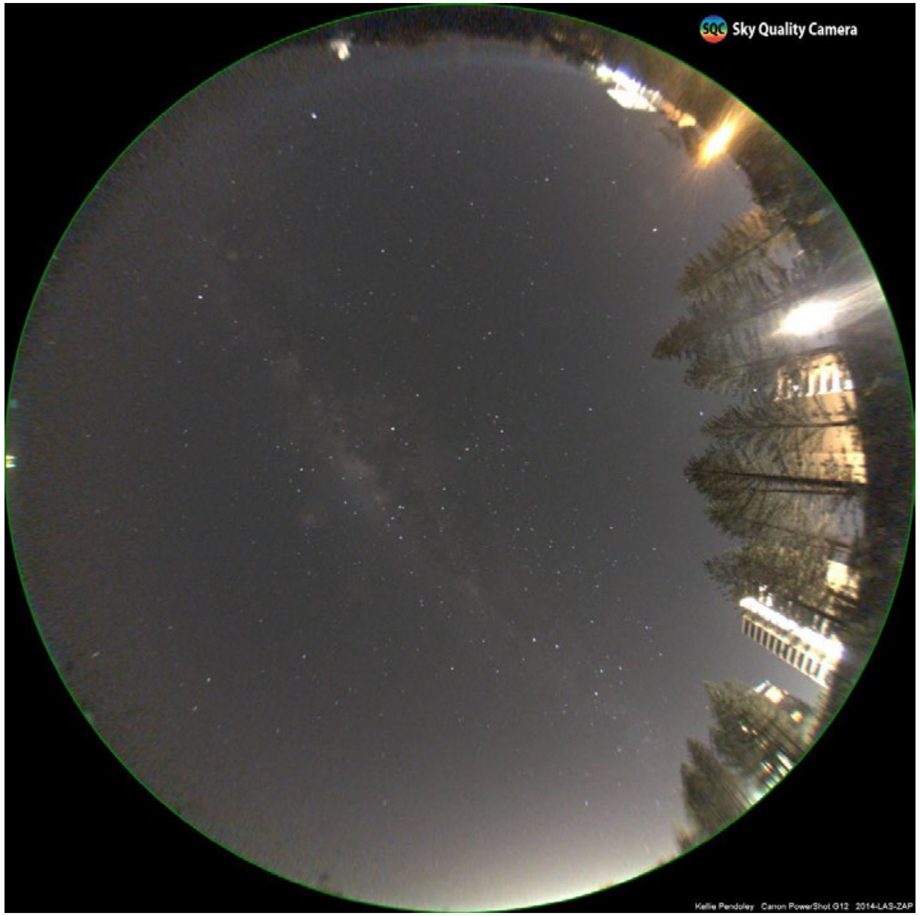



**Figure A14. Sky42 photograph of Buddina (Point Cartwright). Taken on 24th June 2017.**


**Figure A15. Sky42 photograph Mooloolaba in clear conditions. Taken on 24h June 2017.**

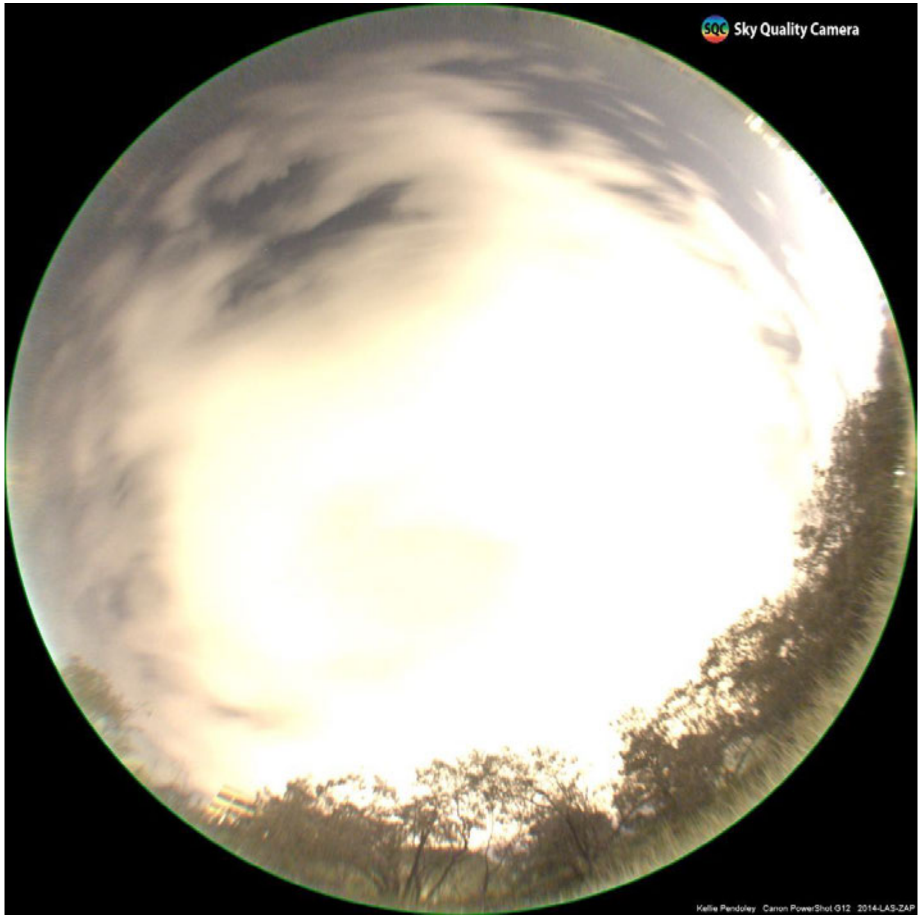



**Figure A16. Sky42 photograph Mooloolaba in cloudy conditions. Taken on 24h June 2017.**


**Figure A17. Sky42 photograph Mudjimba (South) in mostly clear conditions. Taken on 26h June 2017.**

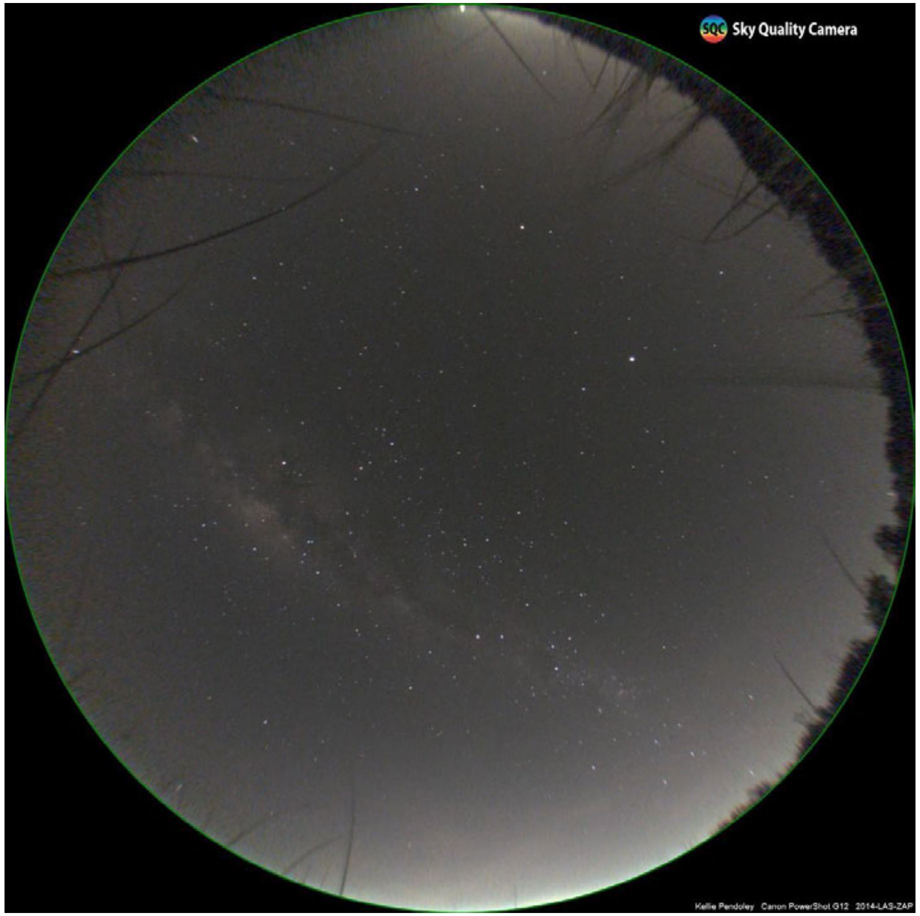



**Figure A18. Sky42 photograph Mudjimba (North) in clear conditions. Taken on 24h June 2017.**

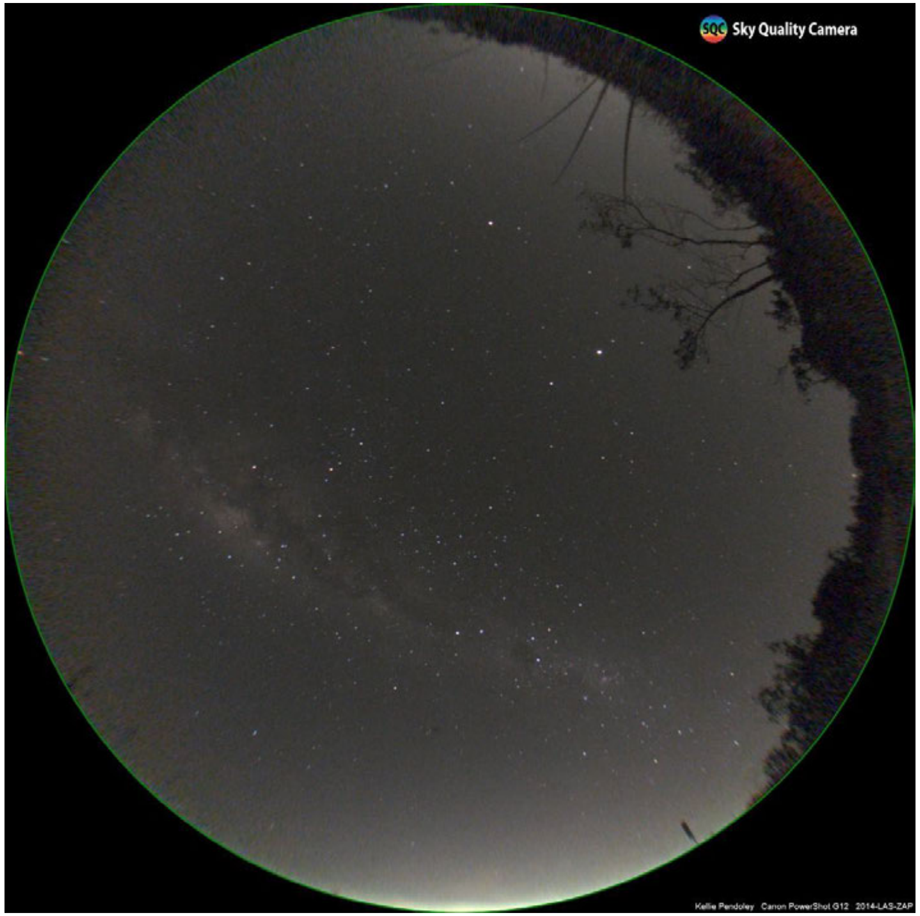



**Figure A19. Sky42 photograph Yaroomba (South) in clear conditions. Taken on 24th June 2017.**

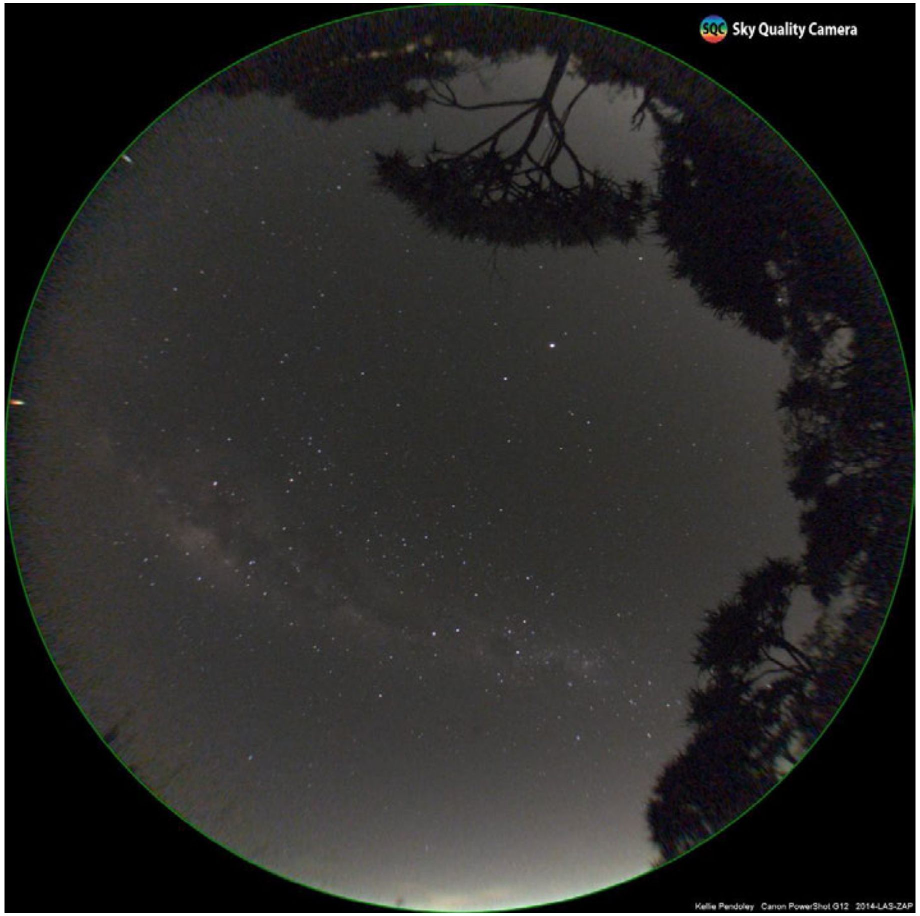



**Figure A20. Sky42 photograph Yaroomba (North) in clear conditions. Taken on 24th June 2017.**


**Figure A21. Sky42 photograph Coolum Beach (South) in clear conditions. Taken on 24h June 2017.**

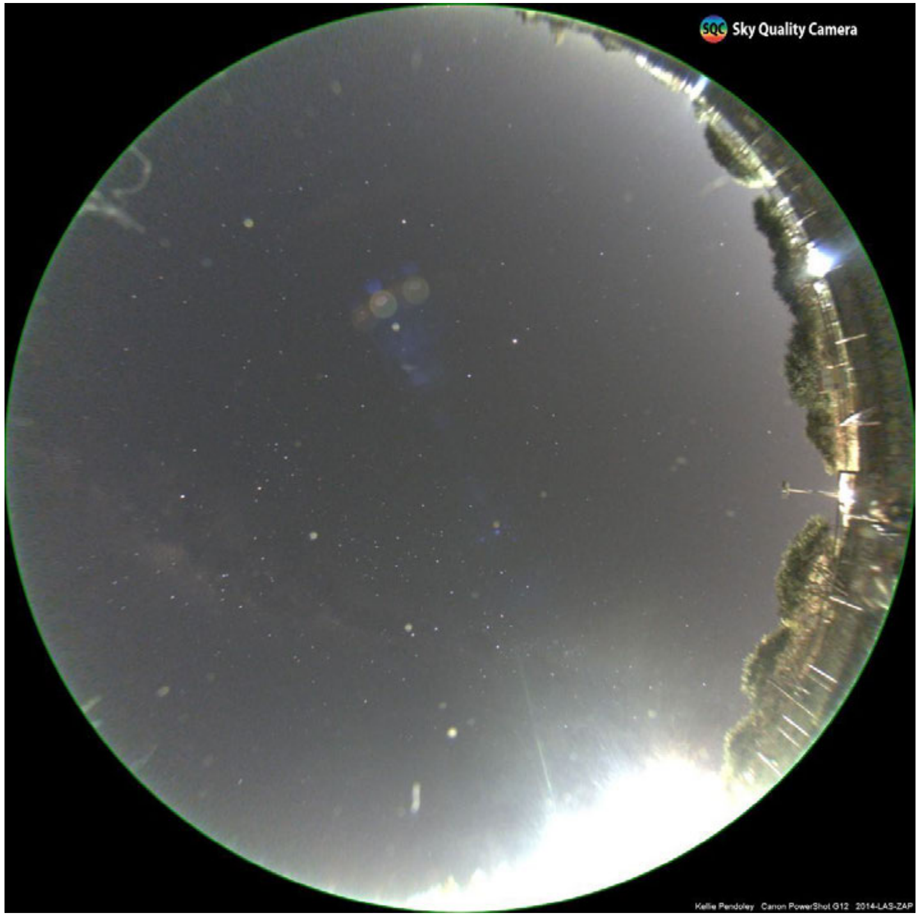



**Figure A22. Sky42 photograph Coolum Beach (South) in clear conditions. Taken on 25h June 2017.**

## APPENDIX C: LOCATION OF MONITORING SITES RELATIVE TO LIGHT POLLUTION (LIGHTPOLLUTIONMAP TOOL OVERLAY)

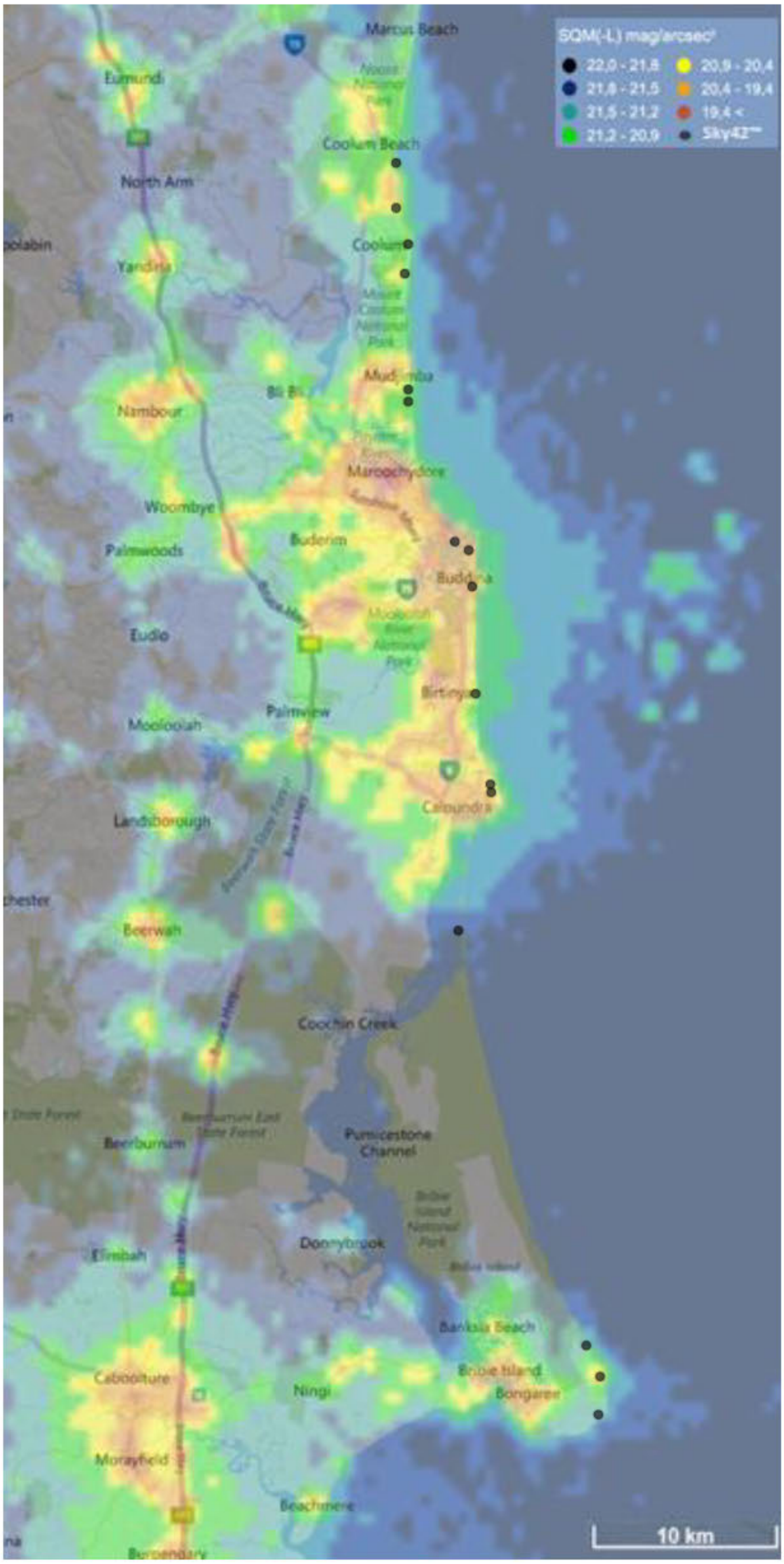



**Image of the Brisbane to Tewantin region generated using the 'lightpollutionmap' tool showing the approximate location of 2017 Sky42™ monitoring sites. Approximate light intensity scale ranges from intense bright light (red: <19.4 mag/arcsec$^2$) to typical rural night skies (dark green: 21 mag/arcsec$^2$) (Source: Stare 2017).**

## APPENDIX D: INDEPENDENT PEER REVIEW- DR PETER HICK

# Review of Pendoley Environmental's Report

# "Artificial Light at Night (ALAN) Benchmark Surveys 2017"

# for SUNSHINE COAST AND MORETON BAY REGIONAL COUNCILS

By Peter Hick

*Dr Peter Hick is a semi-retired former CSIRO Senior Principal Research Scientist, who specialised in his career in spectral and biophysical research for terrestrial and aquatic environments. He has 150+ publications, including books and international journals, some of which are specifically relevant to the light effects on turtles. His PhD was awarded in the field of Marine Physics. His knowledge of local government planning of coastal infrastructure has been gained from his own published coastal geomorphology and climate studies and lately through contributions through Board membership of the Peel-Harvey Catchment Council (15yrs) Rottnest Island Authority (7yrs) and the Peel Development Commission (4yrs).*

*He first became involved in this field in the mid-1990s when the disorientation from lights on offshore and coastal infrastructure, associated with the booming Oil and Gas industry in the NW of Western Australia, was shown to be affecting turtle hatchling survival. He and the CSIRO group that he led, developed the earliest field instruments for spectral analysis and quantification of such light sources. He has closely watched and officially reviewed for both industry and government regulation, the development and application of the current world-class systems for hemispheric night-sky brightness measurement.*

**Addressing the Primary Objectives**

The primary objective of this project was to provide a Benchmark Artificial Light at Night (ALAN) Survey. Night-time surveys at selected sites on monitored nesting beaches along the coastline; a visual assessment of specific light sources visible from each nesting beach and a report providing baseline information on lighting effects along the coastline known to provide important nesting habitat for marine turtles.

This primary objective has been completed.

Specifically, have the following incremental objectives of this project been achieved?

1. Has a benchmark light emission level for use in assessment of development approvals, artificial light at night reduction and community education projects been established?
2. Have the cumulative effects of light on marine turtles been addressed?
3. Will the information assist in making strategic planning decisions along the entire length of the Sunshine Coast Council coastline?
4. Has a reference and quantitative basis for future surveys been provided in order for council to measure, monitor trends and work towards targets outlined within the Sunshine Coast Council Urban Lighting Master plan?
5. Will the results facilitate further discussion and planning about how to mitigate light emissions using this baseline information, particularly in development codes and performance outcomes, in the Sunshine Coast Planning Scheme?

6. Does the report communicate the results of the survey to internal staff, community, consultants and elected representatives?

Clearly the report does satisfy objectives 1 and 2. The quantitative isophotes and tabular summaries do give a measurement of sky brightness and subsequent measurements can be accurately identified and assessed objectively.

The information should provide both Councils with a confident basis upon which to make strategic long-term planning decisions and, if necessary, by-laws with good science supporting best-practice. Objectives 3 and 4 have also been met.

The results should encourage further discussion as requested in 5, but this is very much in the hands of the planners and the role of community participation and education programs. These Councils appear to have a good track record in this aspect with a long-standing recognition of the role of sea turtles in this fragile and pressured coastal environment.

The long-term value of the benchmark provided by this report will stand the test of time and should be highly valued in diffusing subjective arguments posed to internal staff, community consultation and the ultimate decision-makers. The recommendations are sound and should be taken very seriously.

**General comments**

The first sentence on page 15 is probably the most important statement in this report and must be accepted unconditionally. “The science of light quantification is complex”.

Superficially the application of instrumentation such as the Sky42™ and production of images of night sky brightness, may seem relatively straight-forward, as the current availability of imaging technology should make the task reasonably simple. However, nothing could be further from the truth. The quality of the examples produced for this report are extraordinary, both in their quantitative analysis and relevance to biological processes. They do provide confidence for conservation planning.

I have been fortunate to watch the exacting and sometimes frustrating development of the technology of precise spectral measurement of sky brightness and source quantification for over twenty years. The leadership and persistence in the field shown by scientists in the Pendoley team is highly regarded. This report is a clear example of that leadership which is in evidence by the widespread acceptance of the technology as the industry standard for Oil and Gas facility design. It is also genuinely appropriate for the development of Urban Light Master Plans.

The near-shore urban and industrial growth experienced in the minor but not insignificant turtle-breeding beaches of Southern Queensland is coupled with revolutionary development of illuminating capacity of modern lighting sources. However, the recommended solutions relating to choices of light specification as well as foredune shape and vegetation management are realistic and comprehensive for both nesting behaviour and ocean-finding hatchling success. Bench-marking of light sources is vital, as the results of critical decisions taken now, may not become clear for decades.

Figure One of the report clearly show the magnitude of the dilemma and even with this level of urbanisation, significant historic nesting choice and hatchling survival seems to be persisting in this area. The significance and value of this seems to be appreciated by the LGA's and the risks are not underestimated. The choice of camera deployment monitoring sites, always a logistical problem in terms of statistical replication, seems adequately representative of the coastline variability and external illumination sources. More replication may bring refinements but unlikely to alter the outcome.

All coastal atmospheres, especially at night, contain significant water vapour which causes scattering of light. The added contribution of other anthropogenic and natural aerosols magnifies the problem even when cloud, a major light scatterer, is not apparent. The physics of scattering (Mie, Rayleigh and non-selective) as a function of wavelength, is an inevitable complication. This report covers this fundamental aspect in a balanced and forthright manner and the Sky42™ and its associated software is the state-of-the-art technology.

The data presentation in Figure Five provides an excellent example of the quantitative output from this instrument and its innovative software. Being personally unfamiliar with the actual locations, I found the images in Appendix A very helpful in explaining the isophotes, the lighting trial and the raw images in Appendix B. I admit to being confused by the effects of nearby grass on Figure Six until I looked again at Figure Four.

The basic understanding of the sensitive optical spectrum capacity of turtle hatchlings (dominantly shorter wavelengths than human eyesight perception) is also a fundamental design criterion for both the measuring instrumentation and the eventual illumination recommendations. The detailed descriptions of the "Current artificial light profiles" (pages 49-53) provide a good set of practical examples of how relatively simple improvements can be made or realistic judgements assessed on a case-by-case basis.

It is indeed fortunate that the Sunshine Coast and Moreton Bay local governments do have a level of sophistication of understanding the value of monitoring sea turtle behaviour and an established adoption practice to minimise effects of urban lighting and coastal landform management. The examples given in the report should provide a confident basis on which to make adjustments to illumination type, direction and scheduling. The effects of vegetation screening are also quantitatively represented.

The conclusions and recommendations are well supported by the data, are realistic and are fundamental to reasonable natural resource management principles.

The references cited in this report are extensive and comprehensive. They both cover the theoretical and practical science that underpins the conclusions. They also provide the reader with invaluable assemblage of the latest thinking on sea turtle vulnerability, sky-brightness effects on nesting and ocean finding behaviour as well as the latest developments in quantitative monitoring instrumentation.

15 January 2018