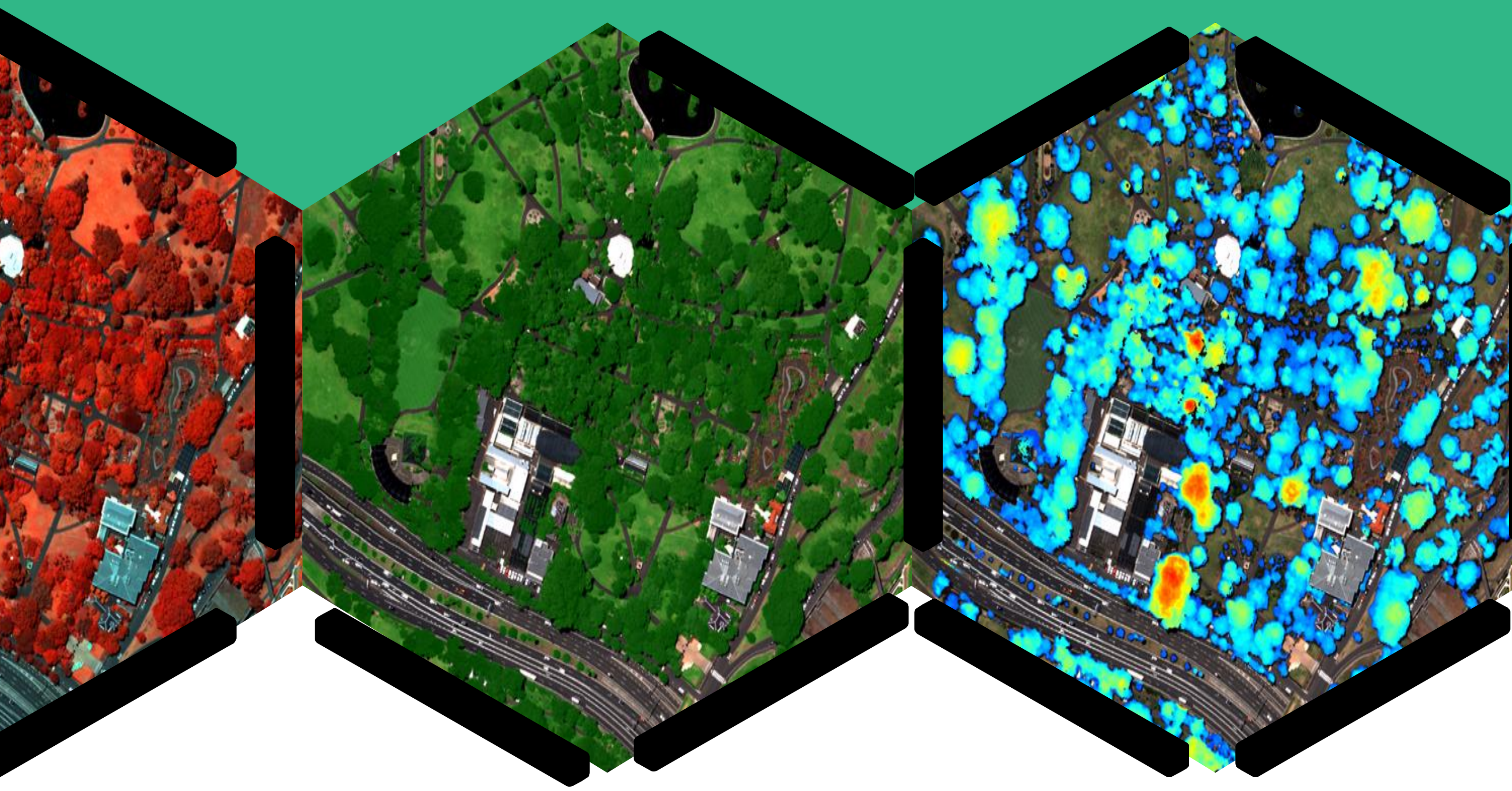
Greater Sydney Canopy and Thermal Assessment 2014 and 2016

Creation of UrbanMonitor® landcover and surface baselines.

Caccetta, P.A., Chia, J., Collings, S., Devereux, D., Traylen, A., Wu, X.

In collaboration with the Office of Environment and Heritage of the Government of New South Wales, and the Royal Melbourne Insititute of Technology



Citation

Caccetta, P.A., Chia, J., Collings, S., Devereux, D., Traylen, A., Wu, X. (2019). Greater Sydney Canopy and Thermal Assessment 2014 and 2016, CSIRO Australia: Creation of UrbanMonitor® landcover and surface baselines.

Copyright

Important disclaimer

Foreword

This project establishes baselines for monitoring the Greater Sydney area for natural resource management and planning using digital aerial photography, satellite and other data. This provides the opportunity to monitor changes in estuarine, river and wetland foreshores; non-irrigated native bush areas; urban canopy cover, irrigation uniformity and efficiency in public and private open space; and areas undergoing urbanization.

This report describes the production of the information derived from digital aerial photography, satellite thermal and other data for environmental and other assessments for the Greater Sydney area, New South Wales, Australia. This includes the generation of baseline information on elevations, ground reflectance, presence of vegetation and its height, and accompanying meta-data. Historic data acquired in 2016 was used representing a relatively recent capture with large geographic coverage, and data acquired from 2014 used as a caparitor year over regions of interest. The information was generated using Urban Monitor® technology developed by the CSIRO. The spatial information produced supports further analysis by State, Local, Commonwealth and other agencies and research organisations involved in greenspace and other assessments. The digital data has been provided to enable it to be combined with other datasets.

The work presented in this report is part of an integrative study conducted with principal partners including the Office of Environment and Heritage (OEH) and the Royal Melbourne Institute of Technology (RMIT). This report describes the information derived and its use by providing examples of quantitative summaries of the information by planning unit, as well as providing examples of the use of the information for visual communication. Results from the broader integrated study are not included here.

Contents

Figures

Tables

Acknowledgments

Funding for the generation of spatial information products was provided by the New South Wales Government as represented by the Office of Envirnment and Heritage (OEH). The work presented in this report is part of a larger study conducted by the OEH, RMIT and the CSIRO.

Executive summary

This project establishes baselines for monitoring the Greater Sydney area for natural resource management and planning using digital aerial photography and satellite data. This provides the opportunity to monitor changes in estuarine, river and wetland foreshores; non-irrigated native bush areas; urban canopy cover, irrigation uniformity and efficiency in public and private open space; and areas undergoing urbanization. The project uses a combination of satellite derived thermal and high resolution land cover information derived from photography. These information provide a means of quantifying the relationship between, for example, green space and land surface temperatures.

This report describes the production of the information derived from digital aerial photography, satellite thermal and other data for environmental and other assessments for the Greater Sydney area, New South Wales, Australia. This includes the generation of baseline information on elevations, ground reflectance, presence of vegetation and its height, and accompanying meta-data. These information were provided in both map and digital formats to the OEH and the RMIT. The purpose of this report is to describe the data, the information products derived, and the interpretation and use of the products.

1 Introduction

This project establishes baselines for monitoring the Greater Sydney area for natural resource management and planning using digital aerial photography, satellite images and other data. This provides the opportunity to monitor changes in estuarine, river and wetland foreshores; non-irrigated native bush areas; urban canopy cover, irrigation uniformity and efficiency in public and private open space; and areas undergoing urbanization. A combination of satellite derived thermal and high resolution land cover information derived from photography were used.

This report describes the generation of spatial information including the generation of baseline information on elevations, ground reflectance, presence of vegetation and its height, and accompanying meta-data. These information were provided in both map and digital formats to the OEH and the RMIT. The purpose of this report is to describe the data, the information products derived, and the interpretation and use of the products.

2 Material and Methods

2.1 Data

Fundamental to monitoring is a consistent time series of data. Having the data geometrically aligned and radiometrically calibrated allows for comparisons through space and time. Using the reporting on nature reserves as an example, this provides information relevant to such questions as "what is the state of this reserve at present relative to its past, and how does this compare with other reserves?”. "How are different areas within the reserve responding to climate, pests, disturbances etc?”. Apart from being a requirement for deriving trend information, geometrically and radiometrically consistent data aids in the analysis and automation of the derivation of class label information such as maps of irrigated and non-irrigated vegetated areas, roads, roofs and trees. Automation is important in this regard because of the volume of data and the fine scale of information which may be derived.

The primary source of data used for the production of the spatial information were:

a) Raw frames of stereo digital aerial photography, the camera meta data, and geometric meta data associated with each frame;

b) Digital surface models generated from primarily from a), and in closed canopy scenarios supplemented with candidate ground points derived from publically available LiDAR surveys;

c) Radiometrically-calibrated true orthophotographs providing estimates of ground reflectance generated from a) and b).

d) Thermal information acquired by the Landsat 8 satellite.

For the purposes of this project, the aerial data were geometrically and radiometrically aligned, and prepared as 1:25,000 map sheets closely corresponding to the standard cadastral map series. Prepared in this way facilitates the data management and use by agencies and other entities using standard software and hardware.

2.1.1 Stereo digital aerial photography

Data were provided by the State and were from acquisitions previously conducted in the years 2014 and 2016. The data were acquired using the Microsoft UltraCam Eagle and/or the UltraCam Eagle Prime camera system (Leberl and Gruber, 2003) flown at a height of approximately 4500m, capturing 4-band (red, green, blue, and near infrared) images, along with panchromatic images. The ground sample distance was approximately 30cm and 10cm for the multispectral and panchromatic data respectively. Images were overlapped along flight lines and among flight lines enabling the generation of digital surface models using stereo photogrammetric techniques.

Ideally photography for monitoring would be drawn from the same season within the year, and specifications to minimize the effect of solar angle and, in particular, shadowing on the images included. The information on date and solar angle of capture are depicted in Figures 1-4.

The 2014 data comprised 11845 image frames of data, acquired within January and early October of 2014. Figure 1 depicts the extent and dates of capture of the 2014 photography, and Figure 3 the solar elevation at capture. For 2014, the following mapsheets were prepared for delivery: 9030NE_riveEE, 9030SE_prosEE, 9130SW_botaEE, 9130SW_parrEE, and 9130SW_parrWW.

The 2016 data comprised 18184 image frames of data, acquired over all seasons between Late February and the end of December of 2016. Figure 2 depicts the extent and dates of capture of the 2016 photography, and Figure 4 the solar elevation of capture.

The field of view was approximately 23 ◦. The dynamic range of the data spectrum as captured by the camera was preserved (i.e. the data were not converted to 8 bit quantisation or compressed using routines converting the data to JPEG formats). Forward overlap of digital frames was of the order of 65- 70% with a 30% side overlap with the neighbouring path.

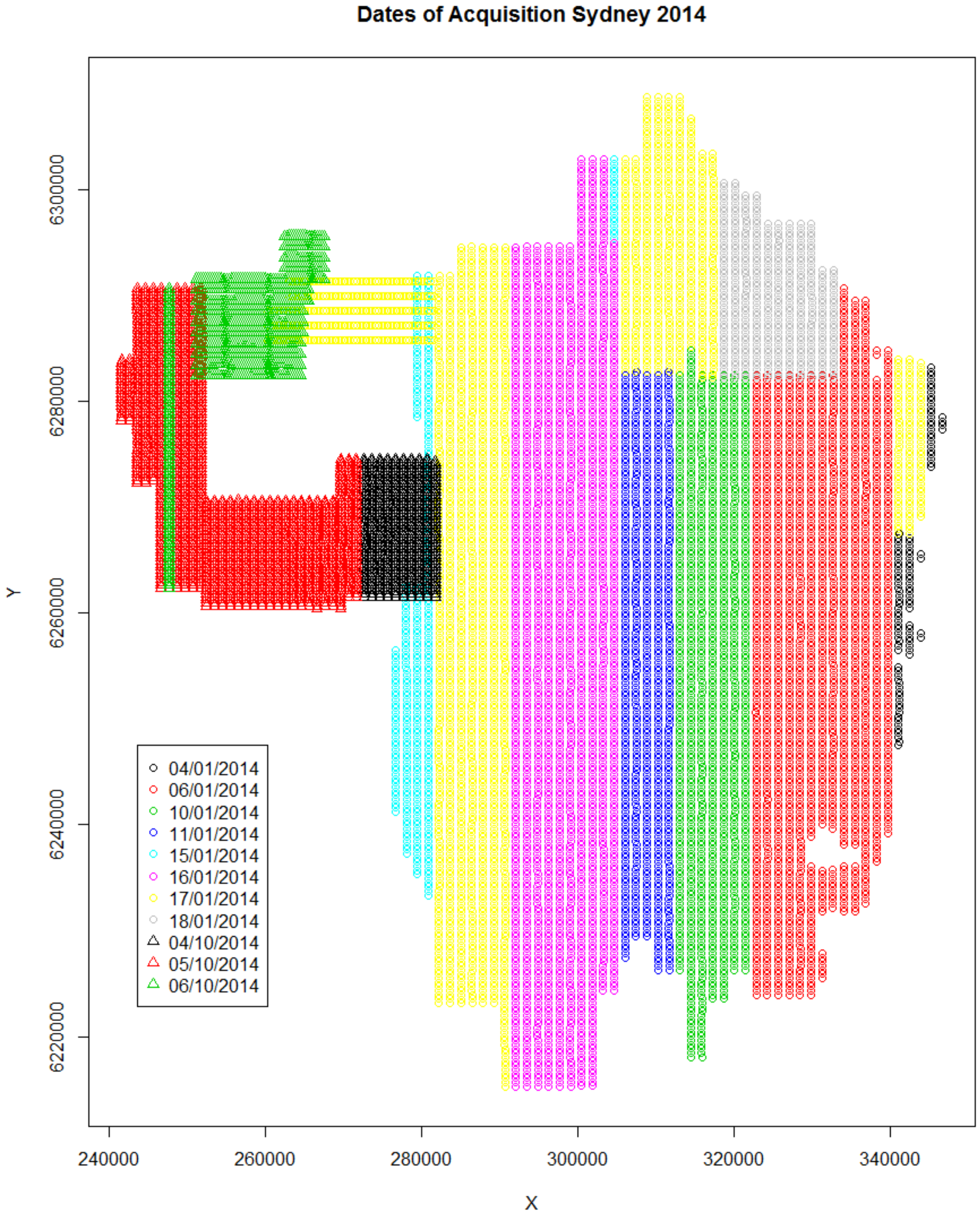


Figure 1 Graphical depiction of the extent and date of aerial capture, 2014. Images were collected in January and (in the west) October.

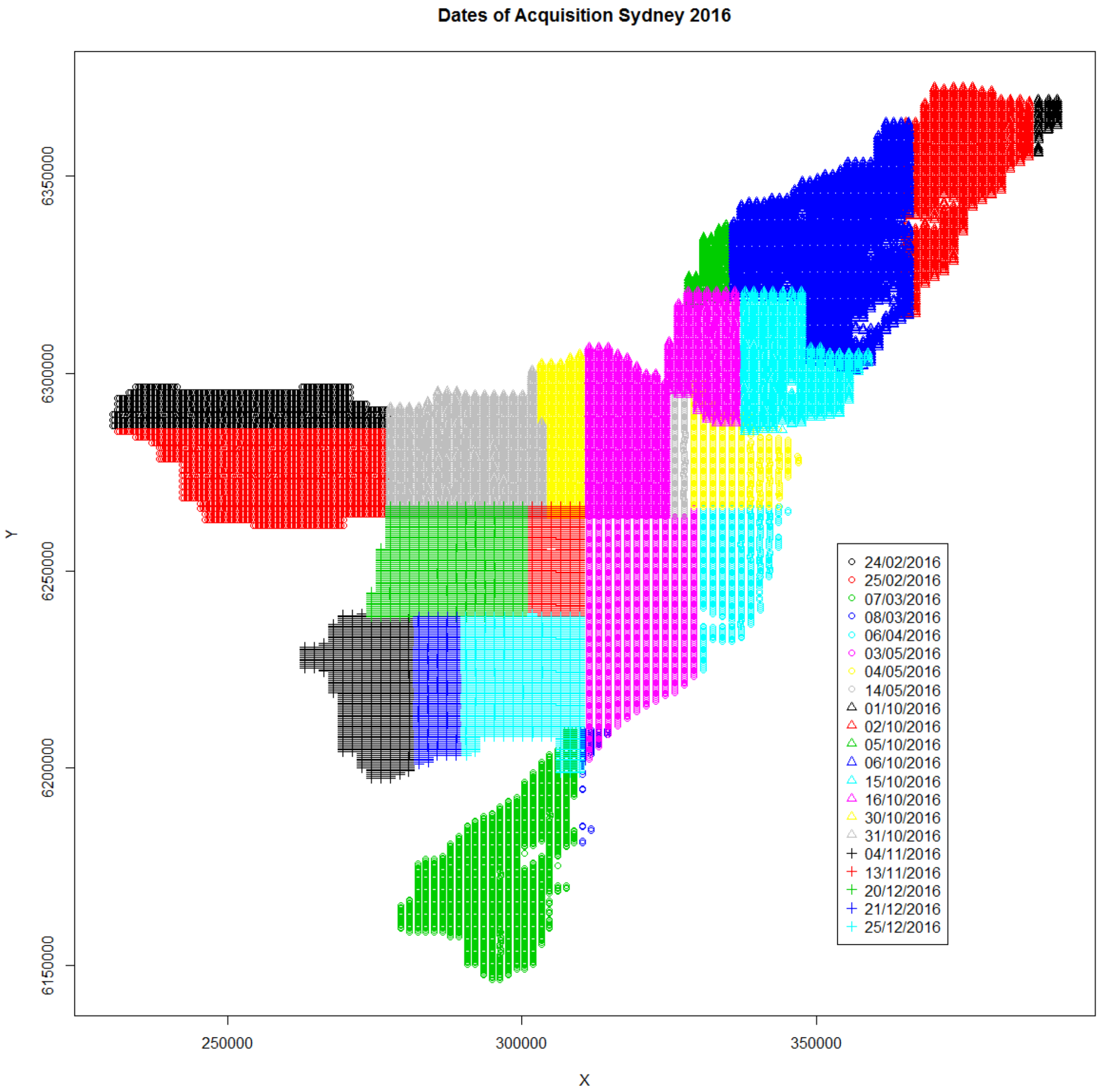


Figure 2 Graphical depiction of the extent and date of aerial capture, 2016.

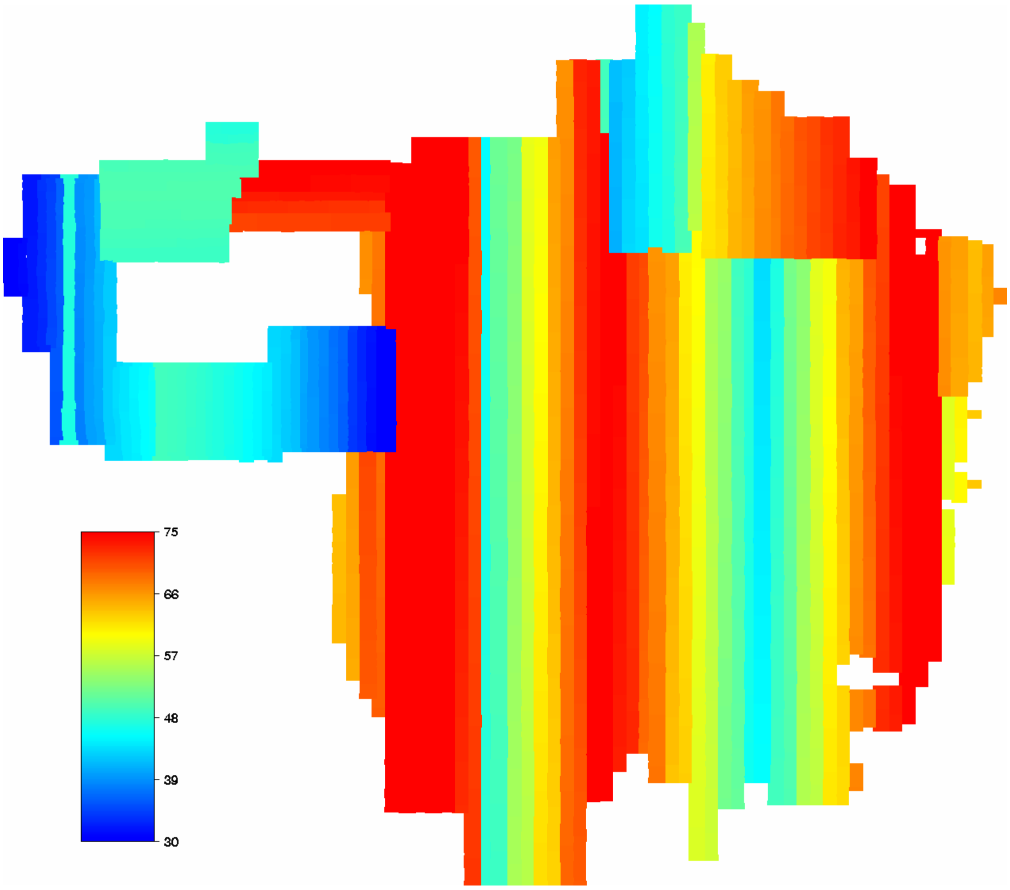


Figure 3 Solar elevation of the 2014 capture (degrees above horizon). Higher solar elevations are preferable to lower solar elevations.

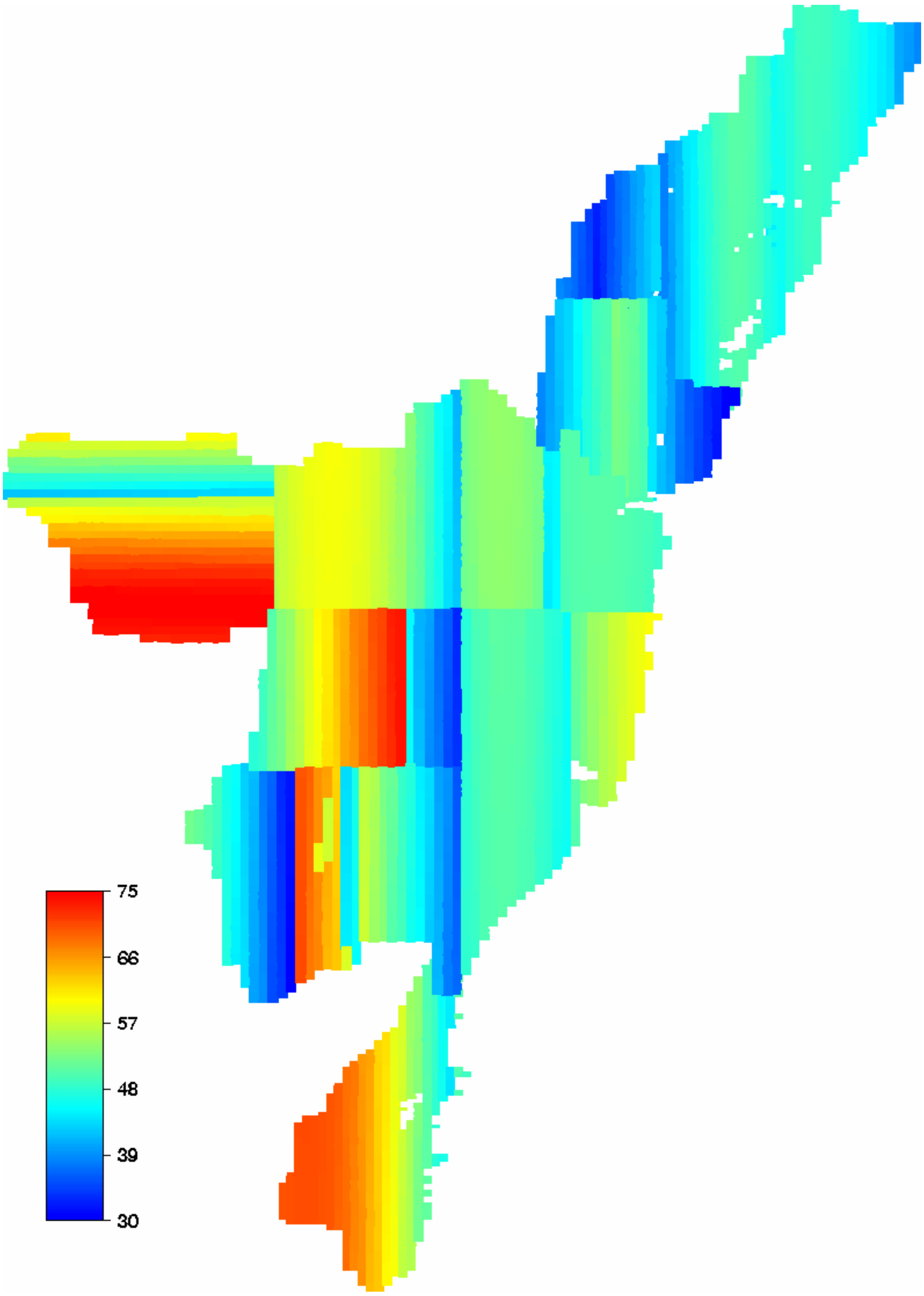


Figure 4 Solar elevation of the 2016 capture (degrees above horizon). Higher solar elevations are preferable to lower solar elevations.

2.1.2 Digital Surface and Ground Elevation Model

A requirement for monitoring change is the accurate geometric correction and co-registration of images. This requires using a very high-resolution digital surface model (DSM) applicable to the image of interest. The DSM is automatically extracted from the stereo images at the native resolution of the images, and then resampled to a resolution of 0.2m.

A ground elevation model (GEM) is generated by removing non-ground surface objects such as trees and buildings from the DSM and then reinterpolating to obtain an estimate of ground height. The GEM is useful for analysis including watershed analysis and as a reference from which to estimate the height of features above the ground, for example the heights of trees. For regions having extended closed canopy cover, ground observations may not be available, or too broadly spaced for accurate interpolation, and candidate ground points from other sources used to improve the ground elevation model .

The first iteration of the ground model was produced using the photogrammetric process. Numerous and large regions of closed canopy resulting in few ground candidate points were noted, and the potential for improving these regions using points from other sources.

Elevation data drawn from the National 5m LIDAR GEM for the region was used for this purpose. The LIDAR GEM source was the "Digital Elevation Model (DEM) of Australia derived from LiDAR 5 Metre Grid" (https://ecat.ga.gov.au/geonetwork/srv/eng/catalog.search#/metadata/89644). The geographic coverage available is depicted in Figure 5. According to the statement on site, the LIDAR GEM's vertical and horizontal accuracy is at least 0.30m and 0.80m repectively.

The 5m resolution LIDAR GEM was resampled using 4 by 4 Kaiser windowed sinc cubic into 0.2m resolution, and when the differences between UM GEM and LIDAR GEM is greater than 2 metres, the LIDAR GEM was used. The LIDAR GEM improves regions having closed forest canopy obscuring creek lines in steep mountain areas; see for example Figure 6.

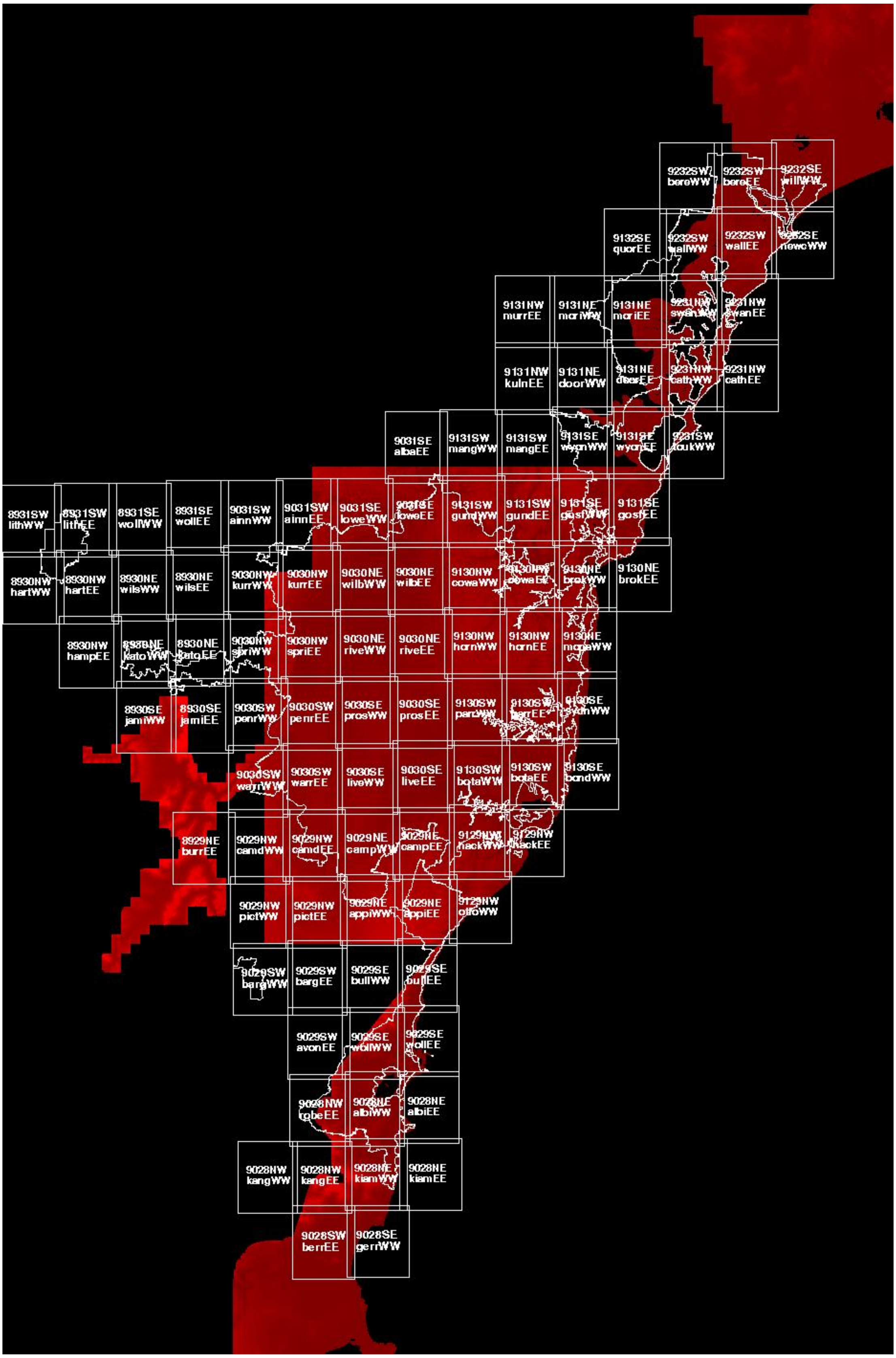


Figure 5 Graphical depiction of the coverage of the Digital Elevation Model (DEM) of Australia LiDAR points considered: LiDAR ground points for the regions depicted in red may be used in the case where the differences between UM GEM and LIDAR GEM is greater than 2 metres.

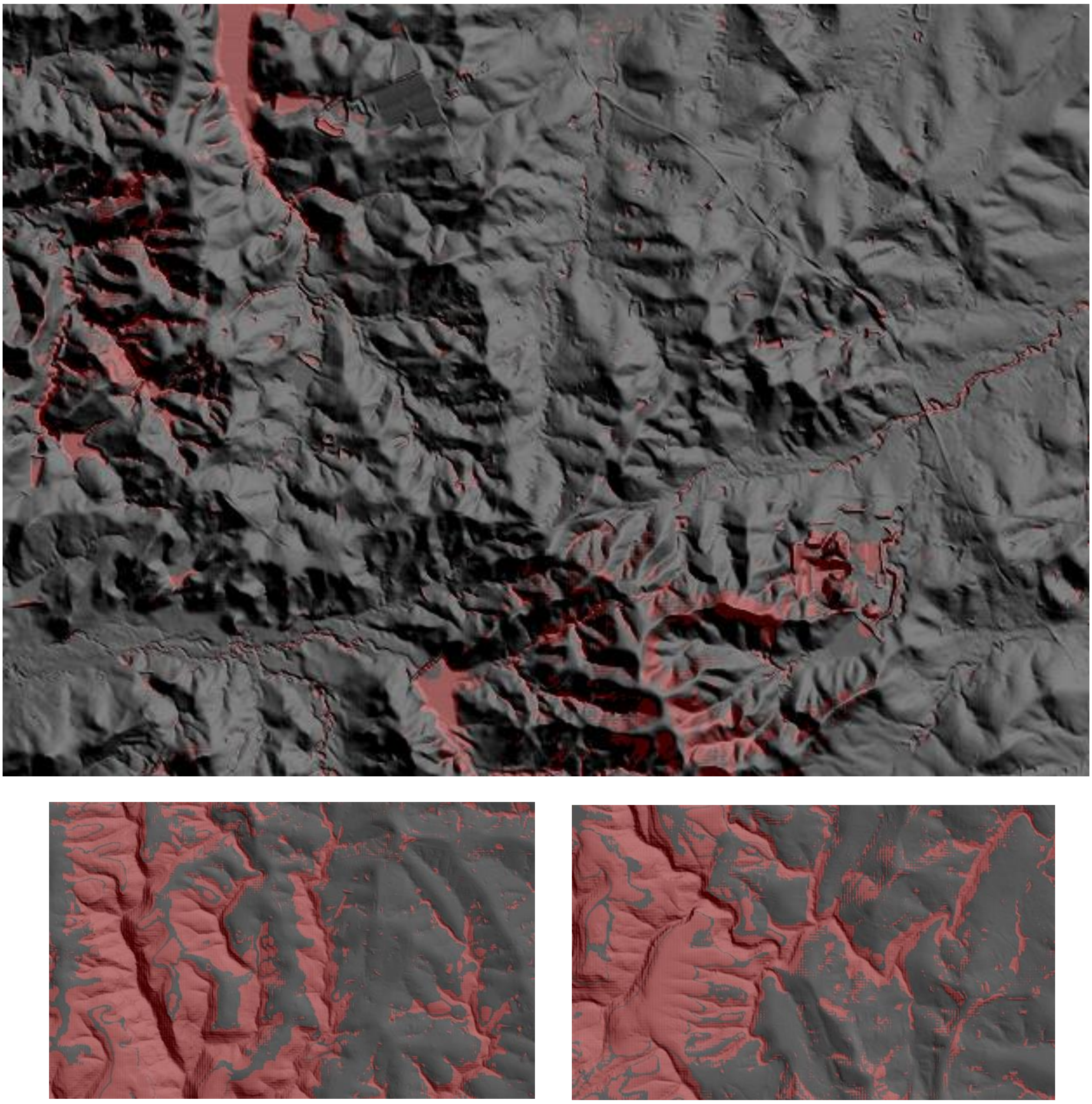


Figure 6 An example of using candidate ground points from LiDAR (red) to augment the high reolution UrbanMonitor surface model (grey). LiDAR ground points for the regions depicted in red were used as the differences between UM GEM and LIDAR GEM was greater than 2 metres. Top: large region example. Bottom: LiDAR estimates improve areas of dense forest canopy obscuring creek lines and in steep mountain areas.

2.1.3 Radiometrically calibrated true orthophotographs

Calibration is required for quantitative comparison of features across geographic regions and there changes over time. This can be achieved by radiometrically calibrating the images to a reference image or to some other standard. The calibration process models for variations in camera parameter settings, atmospheric changes and viewing geometry. As the standard, we have chosen to calibrate to reflectance, and follow the method described by Collings and Caccetta (2013). We note that for direct reflectance comparison with different sensors, the band pass characteristics need also to be taken into account for each sensor, and this step is best addressed when data from multiple candidate sensors is at hand.

A pictorial representation of the effect of calibration is given in Figure 7, demonstrating the improvement in spatial consistency.

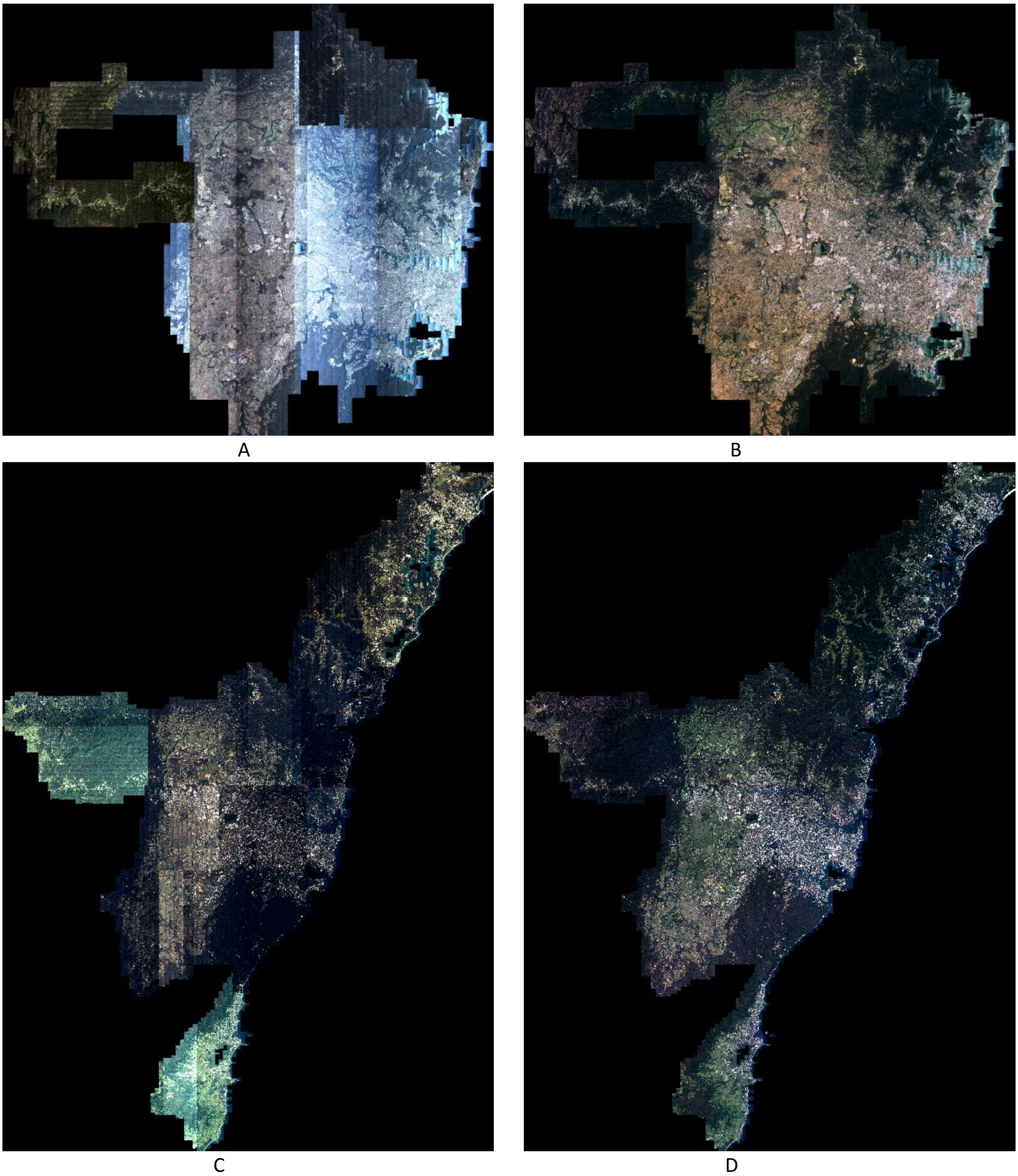


Figure 7 Example of the results of image calibration. A. Non-radiometrically calibrated 2014 orthophotos. B. Radiometrically calibrated 2014 orthophotos. C. Non-radiometrically calibrated 2016 orthophotos. D. Radiometrically calibrated 2016 orthophotos.

Ground reference targets of know reflectance were not available for this acquisition, and therefore the accuracy of the reflectance estimates cannot be directly evaluated. Here we provide the root mean squared (RMS) errors of the differences in the image overlaps, which provides a measure of the spatial consistency of the reflectance estimates. RMS statistics for the corrected and uncorrected overlap statistics are shown below in Table 1. In all bands, the overlap RMS has decreased by 50% or more. The lower RMS errors in the calibrated images demonstrate the improved agreement between the images after calibration.

Table 1 Root mean squared errors in the overlap regions for calibrated and uncalibrated images.

Year	Band	Uncalibrated RMS	Calibrated RMS
2014	Red	88.06	41.85
	Green	93.52	35.73
	Blue	89.73	26.94
	Near Infrared (NIR)	212.32	94.78
2016	Red	122.93	53.46
	Green	118.54	46.82
	Blue	112.46	38.27
	Near Infrared (NIR)	312.77	148.55

2.1.4 Landsat© data, derived Land surface temperature (LST) and Urban Heat Island (UHI)

Estimates of LST and UHI were derived from the thermal channels of the Landsat 8 satellite sensor following the approach described by Devereux and Cacccetta, 2017. For this investigation, LST and UHI were estimated for the Greater Sydney area for the summer periods of 2013/2014 and 2015/2016. The acquisition dates summarised in Table 1 were used in deriving the estimates.

The Landsat sensor captures data for a swath approximately 180km wide as it orbits in a polar orbiting path from north to south, capturing large geographic regions of data within a short period of time. The satellite revisits approximatetly the same geographic area every 16 days. Neighbouring orbits are 8 days apart. For the region considered in this report, data from four orbits (call "paths") was used to complete the geographic coverage of the area. Thus estimates of land surface temperature are derived from multiple dates of data, with temperatures on each date varying with conditions at the time of capture.

Landsat data may be accessed from https://earthexplorer.usgs.gov/.

Table 2 Landsat 8 Images processed. Heavily clouded images were omitted from processing.

Summer Period 2013-2014			**Summer period 2015-2016**		
PATH	ROW	DATE (2013/2014) (yyyymmdd)	PATH	ROW	DATE (2015/2016) (yyyymmdd)
89	83	20131105	88	84	20160123
89	83	20131207	88	84	20160224

89	83	20140313	88	84	20160311
89	84	20131105	88	84	20160327
89	84	20131207	89	83	20151127
89	84	20140329	89	82	20151229
90	83	20131112	89	82	20160130
90	83	20131230	89	82	20160215
90	83	20140115	89	82	20160302
90	83	20140131	89	82	20160318
90	83	20140304	89	83	20151229
90	84	20131112	89	83	20160130
90	84	20131230	89	83	20160215
90	84	20140115	89	83	20160302
90	84	20140131	89	83	20160318
90	84	20140320	89	84	20151213
89	83	20131105	89	84	20151229
89	83	20131207	89	84	20160130
89	83	20140225	89	84	20160302
89	83	20140313	89	84	20160318
89	83	20140329	90	82	20151118
89	84	20131105	90	82	20151204
89	84	20131207	90	82	20151220
89	84	20140124	90	82	20160222
89	84	20140329	90	82	20160309
90	83	20131112	90	82	20160325
90	83	20131230	90	83	20151118
90	83	20140115	90	83	20151204
90	83	20140131	90	83	20160222
90	83	20140304	90	83	20160325
90	84	20131112	90	84	20151204
90	84	20131230	90	84	20160222
90	84	20140115	90	84	20160325
90	84	20140131	91	82	20151109
90	84	20140320	91	82	20151125
			91	82	20151211
			91	82	20151227
			91	82	20160112
			91	82	20160213
			91	82	20160229
			91	83	20151109
			91	83	20151211
			91	83	20151227
			91	83	20160112
			91	83	20160213
			91	83	20160229

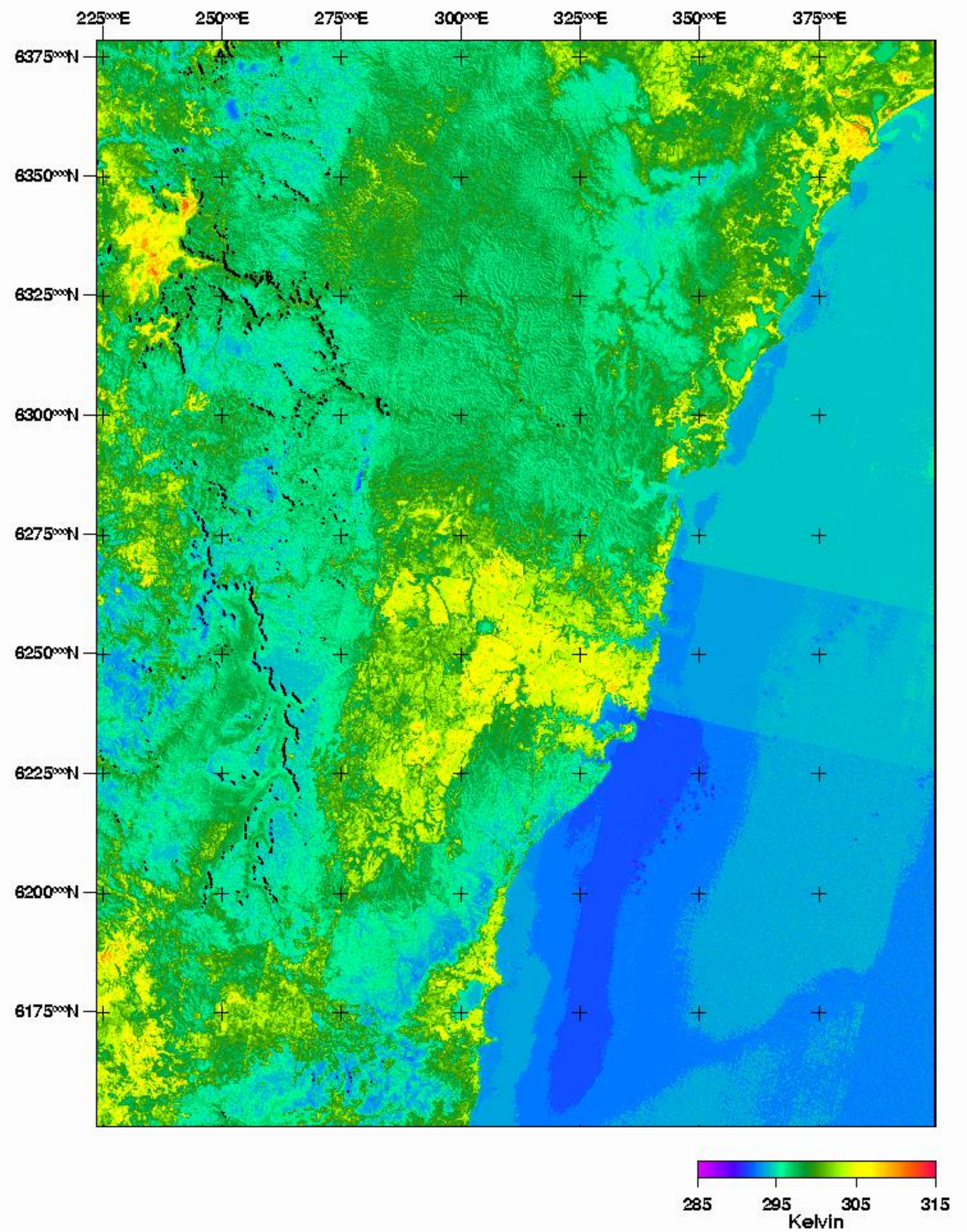


Figure 8 Graphical depiction of Land Surface Temperature for the summer period of 2015/2016. Visible in the figure is some variation in the estimates obtained from different satellite orbits from different dates

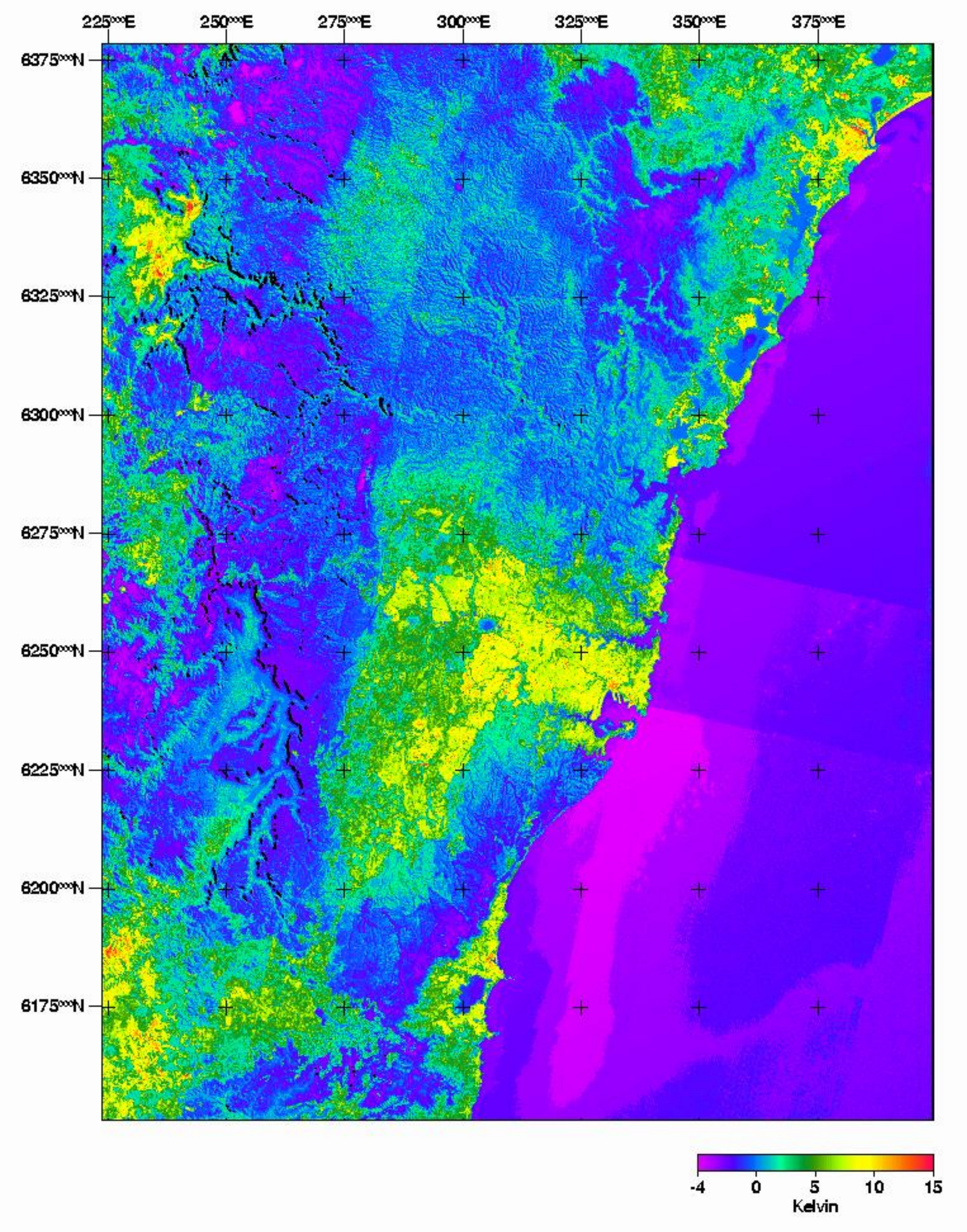


Figure 9 Graphical depiction of Urban Heat Island for the summer period of 2015/2016.

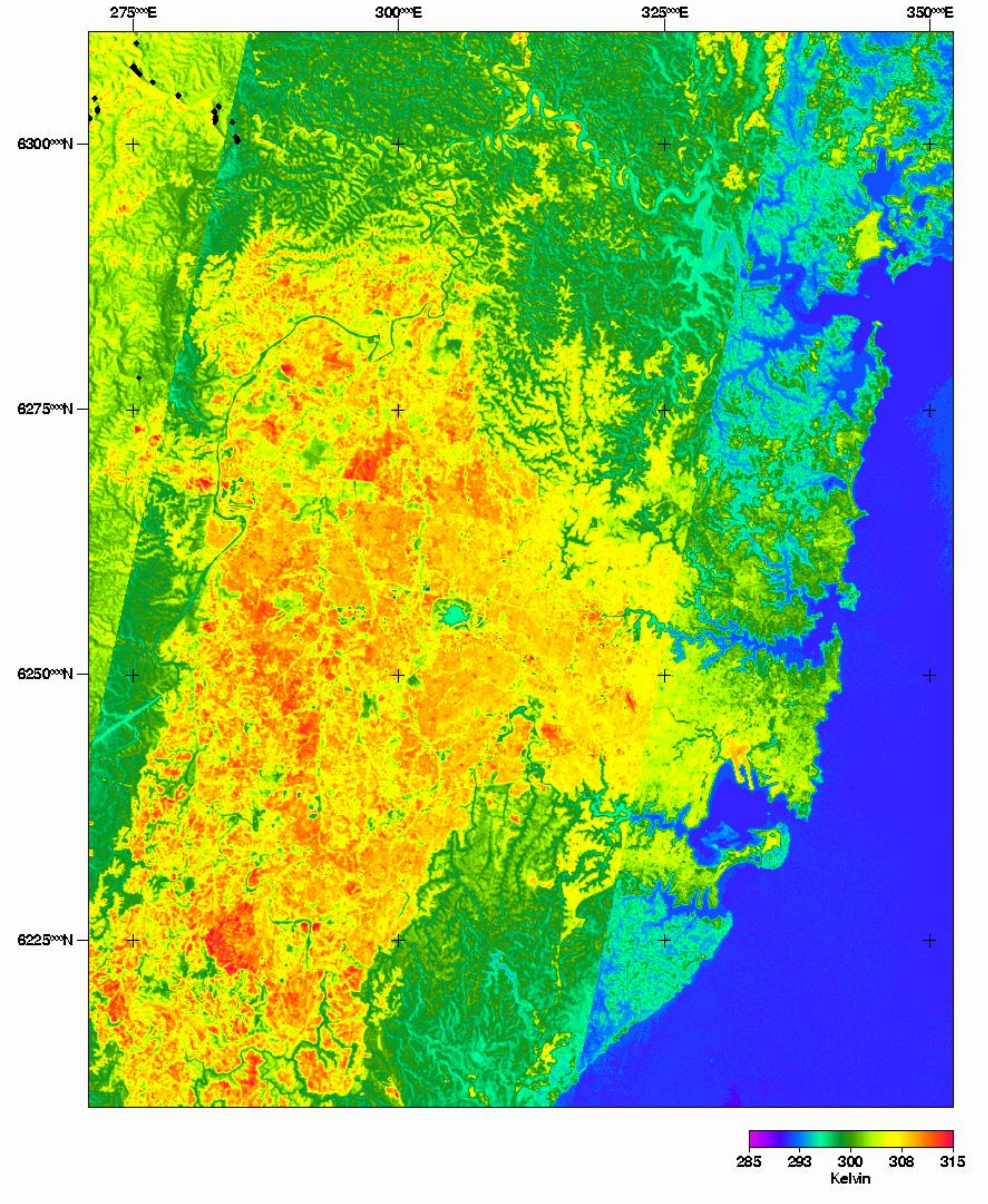


Figure 10 Graphical depiction Land Surface Temperature (LST) for the summer period of 2013/2014. Visible in the figure is some variation in the estimates obtained from different satellite orbits from different dates

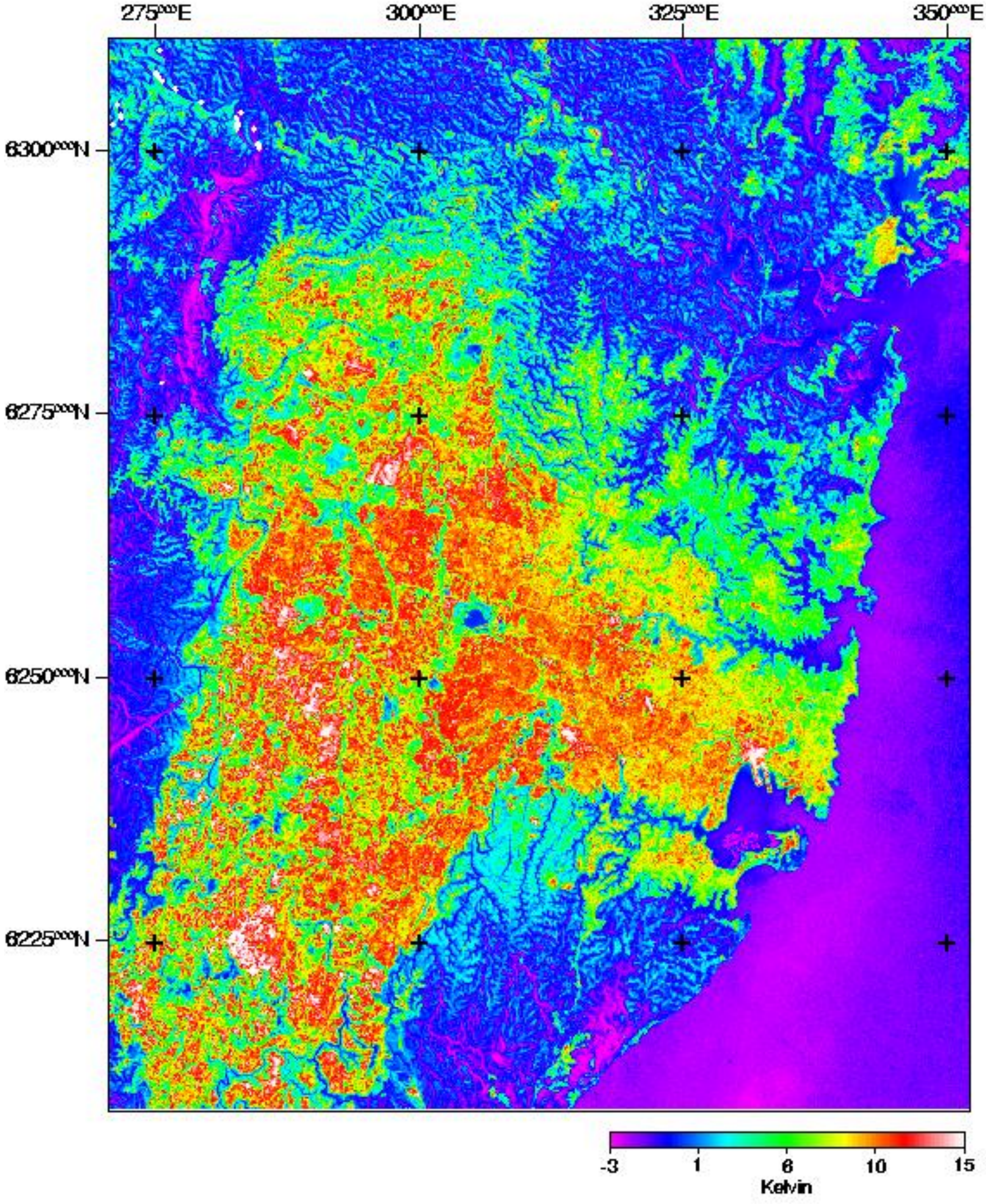


Figure 11 Graphical depiction of Urban Heat Island for the summer period of 2013/2014.

2.2 Hi-resolution Land Surface and Cover Analysis

From the Digital Surface Models (DSMs) and the calibrated orthophotographs, further information may be derived, for example land cover classifications and estimates of ground elevation and tree heights (Caccetta et al. 2015). These were generated by computer algorithms with a high degree of automation with minimal manual intervention.

The steps were:

- a Ground Elevation Model (or GEM) was generated from the digital surface mode (DSM). In this step, candidate ground points were identified (from those that were not ground e.g. trees, houses, etc) and then interpolated to produce the GEM. Note that GEM is often referred to as a digital terrain model (DTM) in the spatial literature.
- A Relative Elevation Model (REM) was generated by subtracting the GEM from the DSM, resulting in elevation relative to ground (which is the reference set to zero)
- A classification of green space was generated using the radiometrically calibrated orthophotographs and the REM. The spectral information identifies active vegetation, including for example grass, bushes and trees, and the REM was used to label these as grass (at ground height) and trees and bushes (above ground).

The products produced for 2014 were

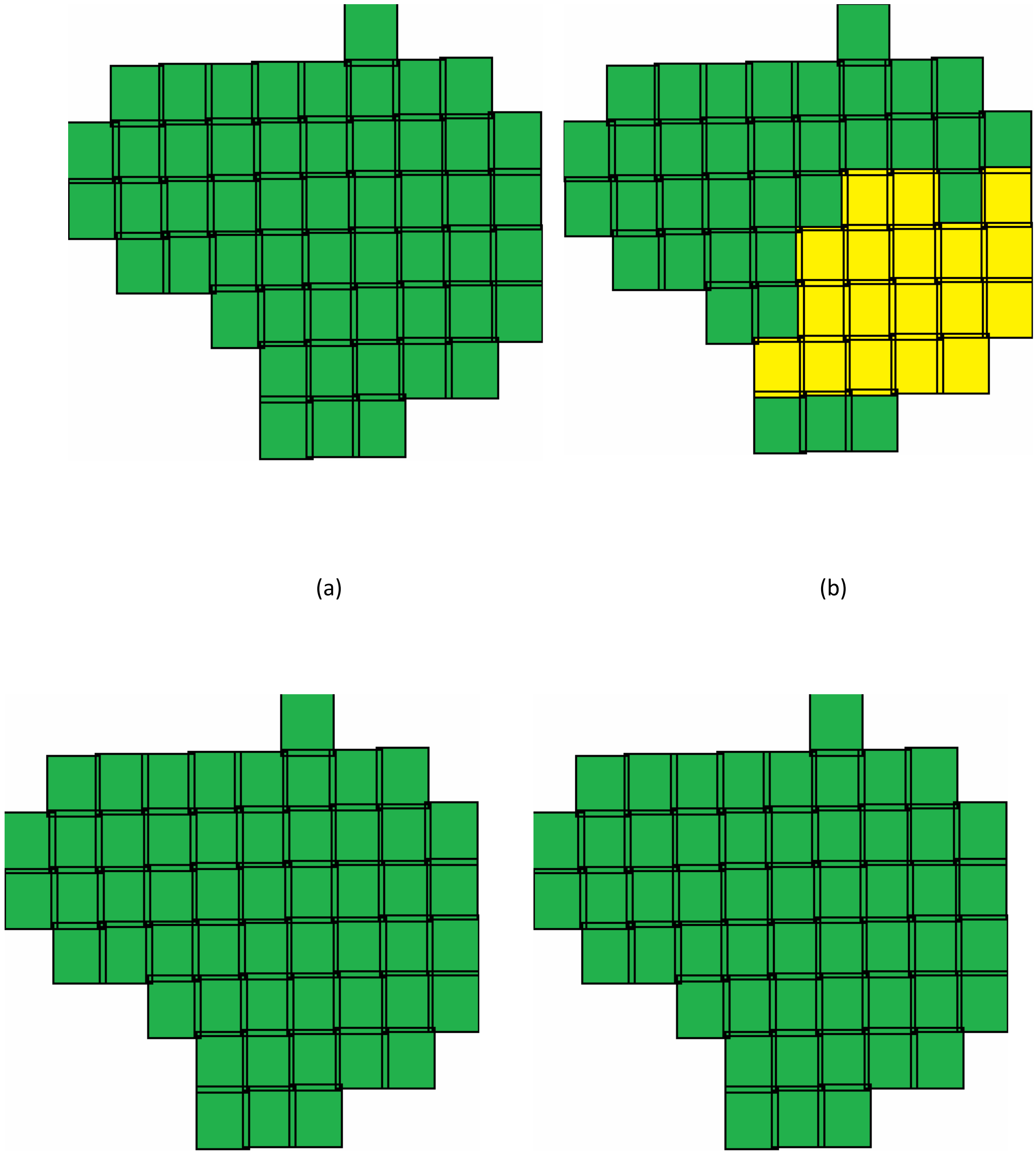
(1) a digital surface model,
(2) a ground elevation model,
(3) a relative elevation model,
(4) a radiometrically calibrated orthomosaic,
(5) a vegetation/non-vegetation classification,
(6) a vegetation height product,
(7) a vegetation index product,
(8) a map of missing data locations,
(9) a grass/non-grass classification, and
(10) a tree/non-tree classification
(11) Meta files including ‘included’ and ‘excluded’ areas.

2.2.1 Processing and quality checking/checking levels

Products for each 1:25,000 tile were processed to 3 different levels:

(1) Automatically generated output, no manual inspection
(2) Automatically generated output, manual inspection for specific errors (e.g. in water bodies, roof tops) carried out. Product has been re-generated.
(3) Automatically generated output, manual inspection and some errors remedied in specific tiles carried out using manual digitisation.

Figures 12 and 13 below show the checking levels for products generated for 2014 and 2016 respectively.



(a) (b)

(c) (d)

Figure 12 Products checking levels for 2014. (a) DSM processing (green = level(2) check), (b) GEM processing (green = level (2), yellow = level(3)), (c) REM processing (green = level(2) check), (d) Vegetation processing (green = level (2) check).

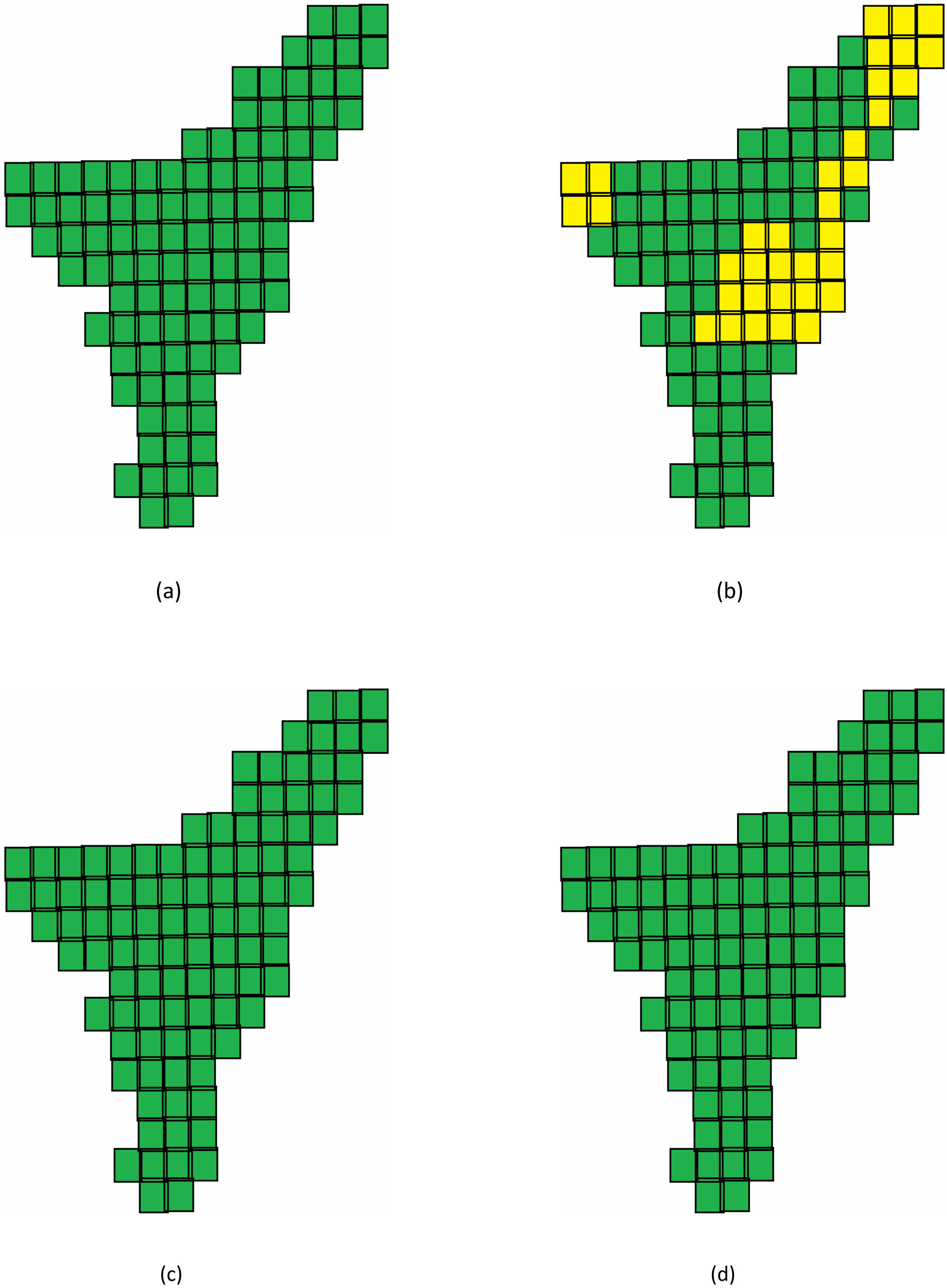


Figure 13 Products checking levels for 2016. (a) DSM processing (green = level(2) check), (b) GEM processing (green = level (2), yellow = level(3)), (c) REM processing (green = level(2) check), (d) Vegetation processing (green = level (2) check).

3 SPATIAL PRODUCT DESCRIPTIONS

3.1 Background and example of use – useful displays

In this section we describe the data layers that were produced and provide a graphical sample of each layer. The information products produced are in a form suitable for further quantitative analysis using a GIS and/or an image processing package, rather than for direct visual display.

3.1.1 Useful displays

Some useful displays may be generated by using combinations of the data layers below. Here we provide some simple compound displays as a sample, noting that it is only a small sample of the combinations that are possible.

Figure 14 Example of compound displays: Top left – orthophoto; Top right – Vegetation/non-vegetation mask in green displayed with sun-shaded elevation model in grey; Bottom left – Irrigated grass mask in green displayed with sun-shaded elevation model in grey; Bottom right – Tree mask in green displayed with sun-shaded elevation model in grey.

Figure 15 Graphical depiction of the left hand digital orthophotograph (right) showing tree height in increasingly 'hot' colours displayed with a sun-shaded elevation model in grey for unvegetated areas.

3.2 Digital Surface Model

This product contains the height above sea level for each pixel/object. Units are in millimetres (mm) above sea level. When compared with the ground elevation model it gives the height above ground surface for each object (e.g. tree heights). The digital surface model can be displayed as a pseudo-colour (below), and as a sunshaded display whcih has proved useful for visual inspection of the edge of features. NULL values (-320 000) correspond to missing, corrupted, or extremely (erroneously) high or low heights, or to locations outside the Urban Monitor extents.

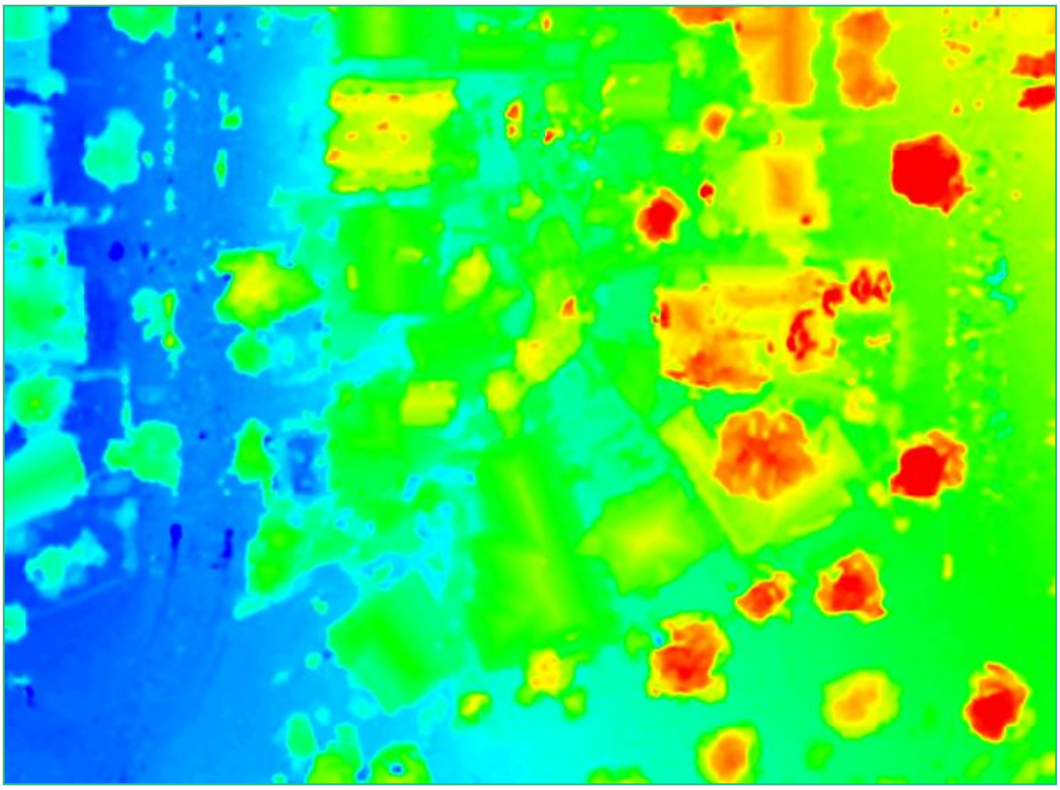


Figure 16 A pseudo-colour display of the digital surface model. Hot colours are high pixels (relative to sea level), cool colours are low pixels.

3.2.1 format

This raster (gridded) data is stored as signed 32bit integers. Units are in millimetres above sea level with the NULL value being -320 000. File names contain the abbreviation *dsm*.

3.2.2 limitations

The stereo matching technique used to create the digital surface model is less reliable where:

(1) there are no objects, or texture (such as large dry lakes)
(2) materials are reflective (eg. water and large glass roofs)
(3) there is movement between two image pairs (eg. cars on roads, water)
(4) the surface discontinuous or thin such as sparse tree crowns and clouds
(5) the location and direction of the camera is incorrect.

Particularly for cloud related errors, cloud shadows may occur without the cloud itself being in the mosaicked multispectral images.

There is some variation in the shape of objects due to the camera angle. This variation is expected to be relatively small but has not been characterised completely.

3.3 Ground Elevation Model

The ground elevation model (GEM) gives the height in millimetres (mm) of the bare ground above sea level. This product is also known as a Digital Elevation Model (DEM). As with the digital surface model, a pseudo-colour is a good display (below). NULL values (-320 000) correspond to missing, corrupted, or incorrect height data.

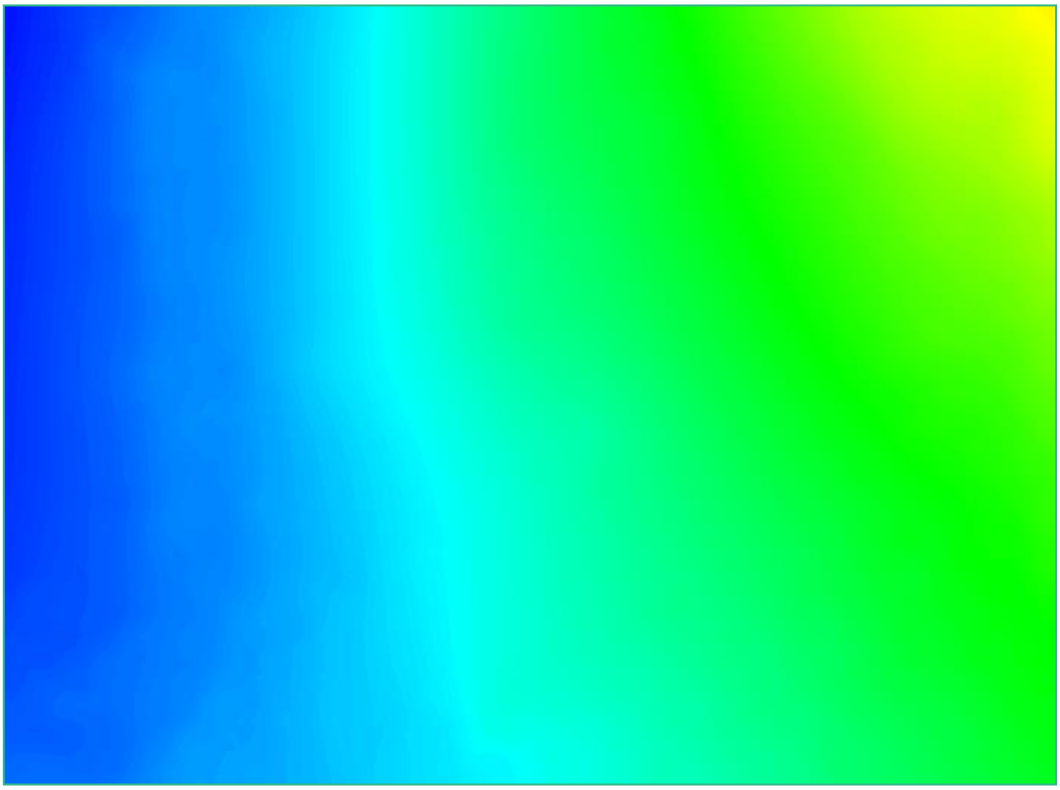


Figure 17 A pseudo-colour display of the ground elevation model. Hot colours are high elevation, cool colours are low elevation.

3.3.1 format

This raster data set is stored as signed 32bit integers. Units are in millimetres above sea level with the NULL value being -320 000 (same as the digital surface model). File names contain the abbreviation *gem*.

3.3.2 limitations

Limitations of the ground elevation can be broadly divided into three categories:

(1) The true ground has sharp variations that the GEM smooths out. This often occurs at bridges, retaining walls, cliffs, highway barriers and the occasional steep dune system. The effects are usually localised and small in magnitude.

(2) The surface occasionally includes roofs of large industrial/commercial buildings and thick plantations forests where the ground is obscured over large areas. Efforts have been made to manually repair most of these errors.

(3) Not enough bare ground leads to knolls, hills, or valleys being omitted. This is known to only occur a few times, and only in extensive dense forests.

3.4 Relative Elevation Model

This product gives the heights of objects relative to the ground. The data is in millimetres, and always positive. This data is used to determine vegetation and building heights. It is often viewed as a pseudo-colour. NULL values (-320 000) correspond to missing/corrupted data or locations outside the Urban Monitor extents. The location of NULL values can be found using the no data mask.

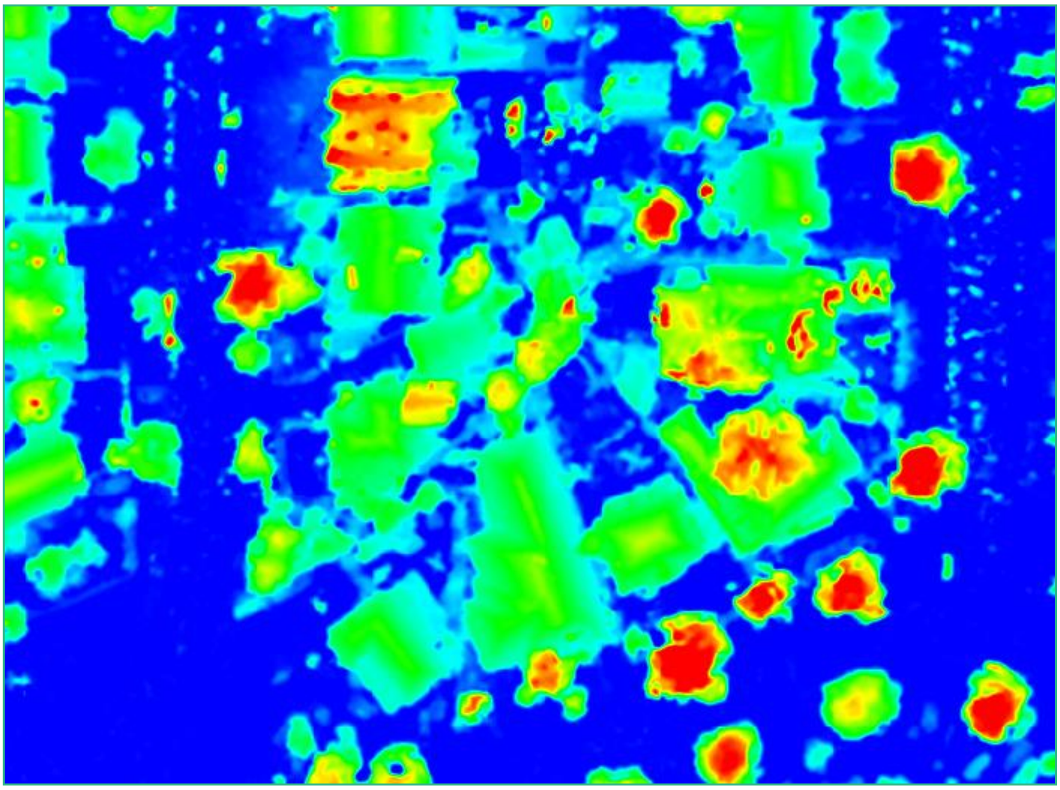


Figure 18 A pseudo-colour display of the relative elevation model. Hot colours represent tall objects; cooler colours are low lying objects/ground.

3.4.1 format

This raster data set is stored as signed 32bit integers. Units are in millimetres above ground with the NULL value being -320 000. The heights are always 0mm or greater. File names contain the abbreviation *nsm*.

3.4.2 limitations

The limitations of the relative elevation model are directly related to the limitations of the DSM and the GEM. It is less reliable where:

(1) The area is flat with no objects, or texture (such as large dry lakes)
(2) the materials are reflective (eg. water and large glass roofs)
(3) there is movement between two image pairs (eg. cars on roads, water). Often the heights in water are wildly incorrect with values of 100m and higher
(4) the surface is discontinuous or thin such as sparse tree crowns and clouds
(5) the location and direction of the camera is incorrect.

And where roofs or forest canopy are included in the GEM then the relative elevation model is close to 0. Similarly when not enough bare ground leads to knolls, hills, or valleys being omitted from the GEM it causes the relative elevation to by incorrect.

3.5 Multispectral, Radiometrically Calibrated, True Orthophotographs

These images contain four bands of spectral data, are calibrated to ground reflectance and are orthorectified. The bands are red, green, blue and near-infrared. The order is different to normal multispectral data because band 4 corresponds to near-infrared data. For vegetation related work a false colour display are useful. The true colour display is also quite useful, especially for those unfamiliar with remote sensing.

Figure 19 (Top) False colour image (red = band 4; green= band 1; blue=band 3). (Bottom) True colour image (red = band 1; green = band 2; blue = band 3)

3.5.1 format

This raster data is stored as signed 16bit integers. It contains 4 bands:

Band 1: red

Band 2: green
Band 3: blue
Band 4: near-infrared

The units are in percent ground reflectance x 100. So ideally the spectral values range from 0 to 10 000, however the statistical nature of the calibration means that some values are outside this range.

NULL pixels are represented by all the reflectance in all 4 bands being set to 0.

File names contain the abbreviation *dom*.

3.5.2 limitations

The calibration cannot overcome illumination differences caused by cloud and cloud shadows. The appearance of actual clouds in the mosaic is very rare. However shadows cast by clouds are fairly frequent in some areas.

At very fine scales errors in the DSM can cause orthorectification errors make buildings and vegetation appear distorted.

The statistical nature of the calibration method means that spectral values can sometimes be negative. Usually it is acceptable to think of these as 0, but sometimes they contain useful data.

3.6 Vegetation/non-vegetation (two class) classification

This product classifies pixels into either green growing vegetation, or everything else. Green trees and irrigated lawns have a value of 1, all other areas cover types, including shadows and NULLs have a value of 0. Areas where there is no spectral data can be found using the no data mask product.

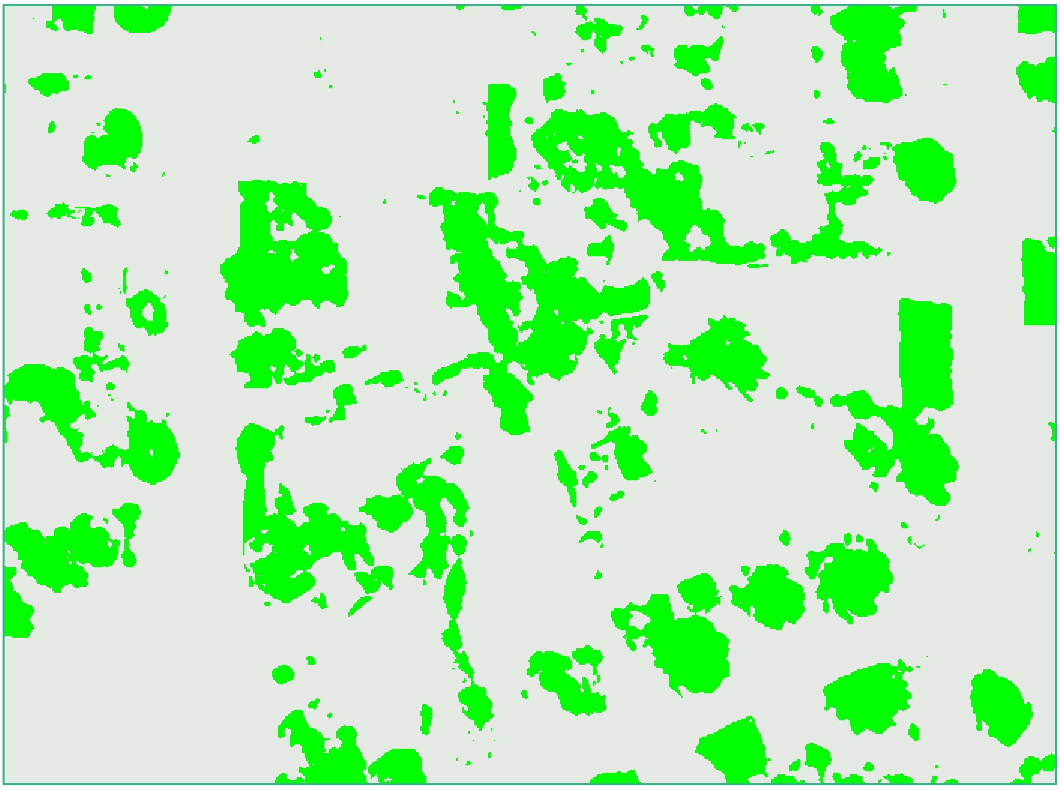


Figure 20 The vegetation/non-vegetation mask (green = vegetation, grey = everything else)

3.6.1 format

This raster data is stored as unsigned 8bit integers. Pixels determined to be vegetation have been assigned a value of 1. All other pixels, including missing data are assigned a value of 0 which corresponds to the NULL value of the dataset. File names contain the abbreviation *veg*.

3.6.2 limitations

The vegetation mask does not include dry, brown vegetation such as heath, brown grass, forest litter or brown trees. Shadowed, green growing vegetation is also not included.

The classification relies heavily on the multispectral images and it inherits many of its errors: vegetation is occasionally missed in cloud shadows; it is completely missed in areas of cloud; and ortho-rectification issues can cause slight location inaccuracies. However the vegetation mask performs well over water, it is very rarely labelled as vegetation.

The classification is also confused by green synthetic materials (tennis courts), blue materials (empty swimming pools and blue roofs) as well as dark (or black) roofs.

Some subtle calibration differences has caused over classification in some forested areas.

3.7 Vegetation height

This product contains the height of vegetation pixels relative to the ground in millimetres (mm). It is best viewed as a pseudo-colour. All non-vegetation pixels or pixels without height/spectral information are NULL.

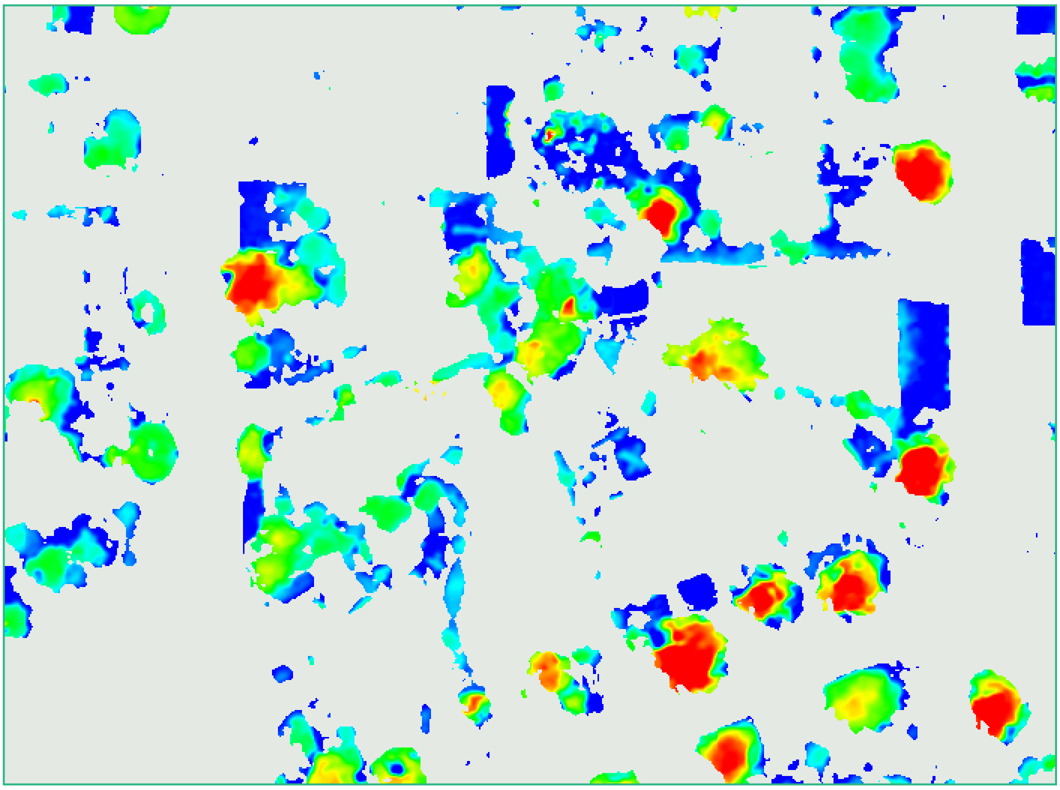


Figure 21 Hot colours are tall trees; dark, cool colours are grasses/low-lying vegetation

3.7.1 format

This raster data set is stored as signed 32bit integers. Units are in millimetres above ground with the non-vegetation and missing data represented by the NULL value of -320 000. The heights are always 0mm or greater. File names contain the abbreviation *vht*.

3.7.2 limitations

This product inherits its limitations from the vegetation classification and the relative elevation model. Of particular importance to the vegetation height data are:

(1) When the GEM includes forest canopy the result is erroneous
(2) Where dense forests obscure real features in the terrain then the tree heights will show taller or shorter regions.
(3) Sparse tree crowns that are missed in the DSM result in vegetation with a 0 score.
(4) For extremely tall buildings, vegetation on the occluded side of the building can be assigned very tall heights.

3.8 Vegetation Index

This is simply the normalised digital vegetation index (NDVI) calculated by *(b4-b1)/(b4+b1)* for every vegetation pixel (with robust handling of negative values). It ranges from -1 to 1, although most vegetation pixels will have an index greater than 0.2. High values relate to dense, actively transpiring vegetation (e.g. irrigated areas) and low value to sparse or dormant vegetation.

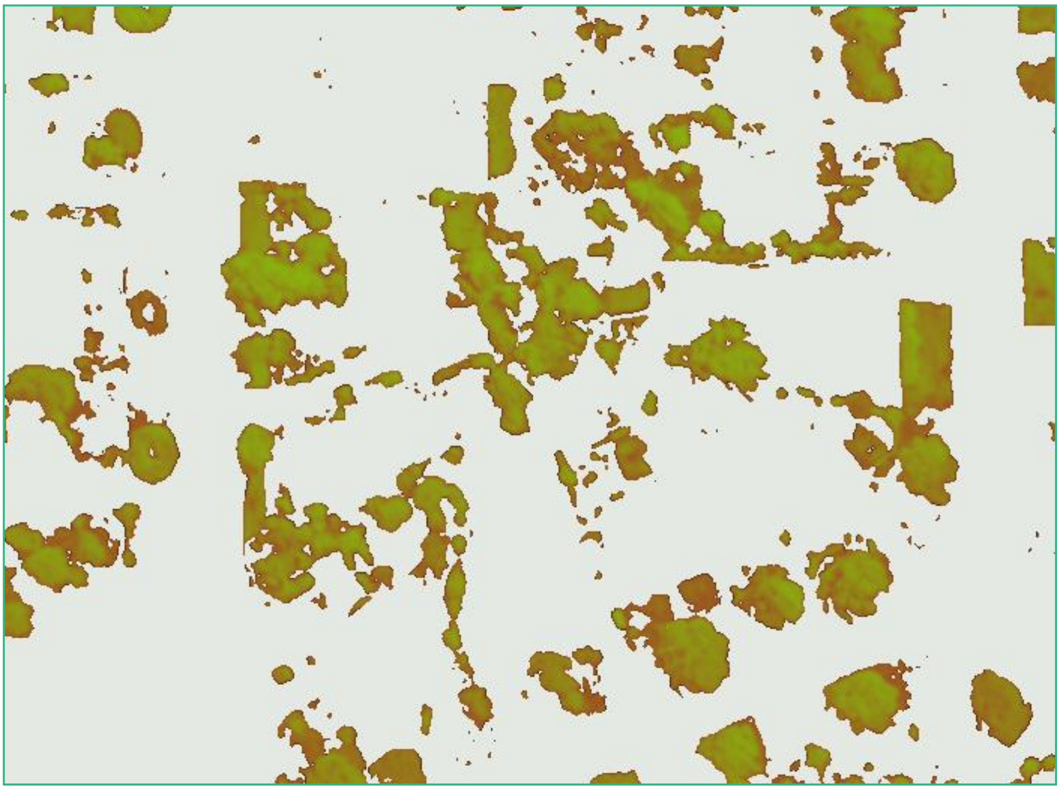


Figure 22 The vegetation index. Green colours have high index, browner colours correspond to low index. White is non-vegetation.

3.8.1 format

This raster data set is stored as IEEE 4byte reals (floating points). The data ranges from -1 to +1. Pixels not in the vegetation class (from the vegetation/non-vegetation classification) are NULL. File names contain the abbreviation *vin*.

3.8.2 limitations

The vegetation index contains a lot of variation, and often contains obvious changes between flight line boundaries due to calibration differences. The index in moisture-rich areas can be lower than it should be due to water absorbing near-infrared radiation.

3.9 No data mask

This product is useful for displaying the location of missing pixels for all the other products except the DSM and GEM. The values represent:

0=no missing data,
1=height data missing (either dsm, gem or both),
2=missing spectral data and
3=missing both spectral and height data

To find missing data for the vegetation mask and vegetation index products, a union of class 2 and class 3 was used. Missing data in the relative elevation model would be the union of class 1 and class 3. The vegetation heights, grass mask, and tree mask rely on both the relative elevation model and the vegetation classification so the appropriate missing data mask would be the union of classes 1, 2 and 3.

Figure 23 A no data mask, with a true colour image behind. Blue = missing multispectral data only; red = missing both multispectral and height information.

3.9.1 format

This raster data is stored as unsigned 8bit integers.

0 (also the NULL value) corresponds to pixels that have both spectral and height data
1 corresponds to pixels that have height data (in the ndsm, gem and dsm) but no spectral data

2 corresponds to pixels that have spectral data but no height data.
3 corresponds to pixels have neither height data, nor spectral data.

File names contain the abbreviation *msk_nod*

3.10 Grass and low bush mask

This is a mask of all the vegetation below 0.5m in height and it is best viewed as a bright green layer.

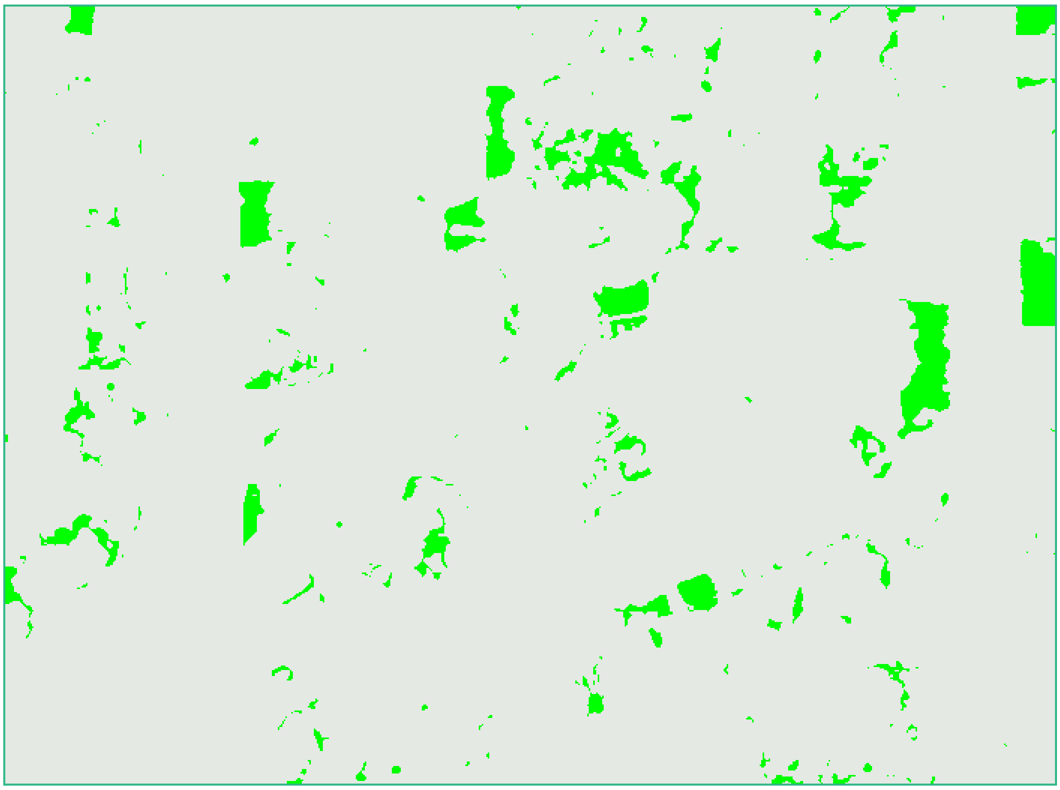


Figure 24 The grass and low bush mask (green = grass, grey = everything else)

3.10.1 format

This raster data is stored as unsigned 8bit integers. Pixels determined to be vegetation close to the ground have been assigned a value of 1. All other pixels, including missing data are assigned a value of 0 which corresponds to the NULL value of the dataset. File names contain the abbreviation *grs*.

3.10.2 limitations

The grass and low bush mask is restricted by the limitations of the vegetation height data. For example sparse-crowned trees can appear as grass. As with the vegetation mask dry heath and brown grass are not included.

3.11 Tree mask

The tree mask is a mask of all the vegetation greater than 0.5m in height and it is best viewed as a bright green layer.

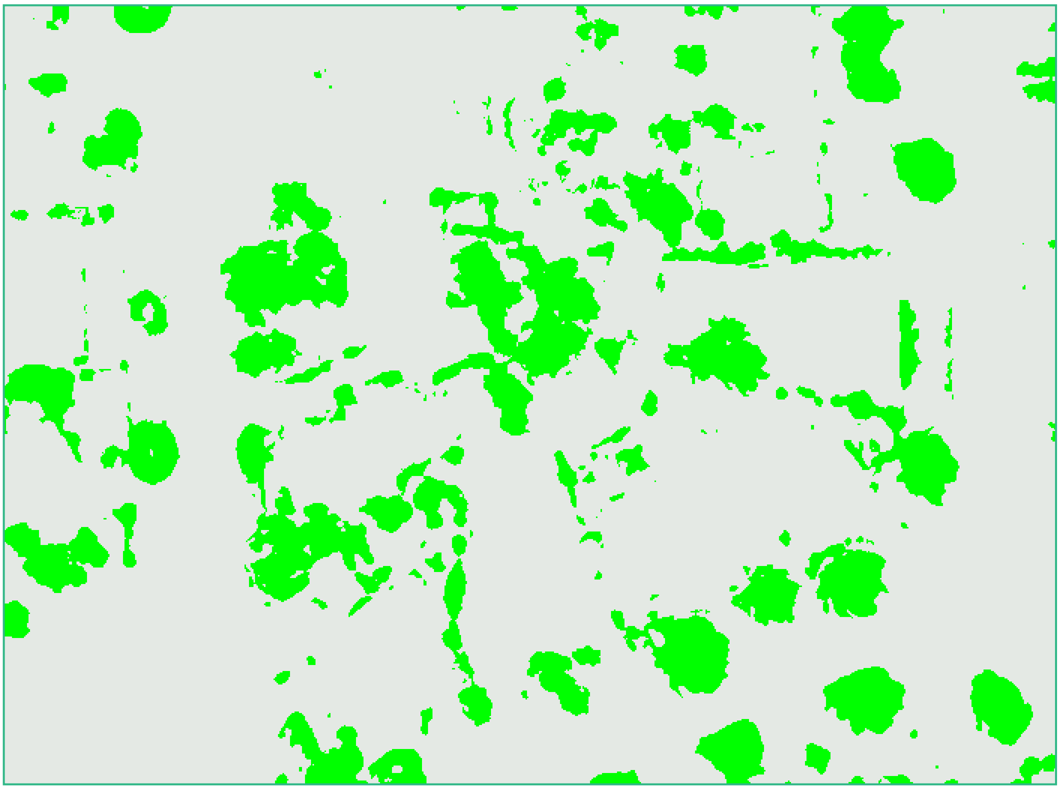


Figure 25 The tree mask (green = tree, grey = everything else)

3.11.1 format

This raster data is stored as unsigned 8bit integers. Pixels determined to be vegetation above the ground have been assigned a value of 1. All other pixels, including missing data are assigned a value of 0 which corresponds to the NULL value of the dataset. File names contain the abbreviation *tre*.

3.11.2 limitations

The tree mask is restricted by the limitations of the vegetation height data. For example sparse-crowned trees will not appear in the tree mask.

4 METADATA AND NAMING CONVENTIONS

This section describes how the Urban Monitor Melbourne area is divided into tiles and the file naming convention used for the products and tiles.

4.1 Map sheet Extents

Urban Monitor (Sydney) valid map tiles for year 2014 are shown in Figure 26 and valid map tiles for year 2016 are shown in Figure 27. The map tile extents are based on 1:25,000 cartographic map extents. The map tile coordinates are justified to allow certain overlaps with adjacent map tiles or/and extend to cover important features such as coast areas. The map coordinate system is based on GDA94 (datum) and MGA56 (projection). All the map tile names are based on the national standard map identifications and names. The coordinates for each map tile and map tile for the valid map tiles for year 2014 are listed in Table 3 and valid map tiles for year 2016 are listed in Table 4.

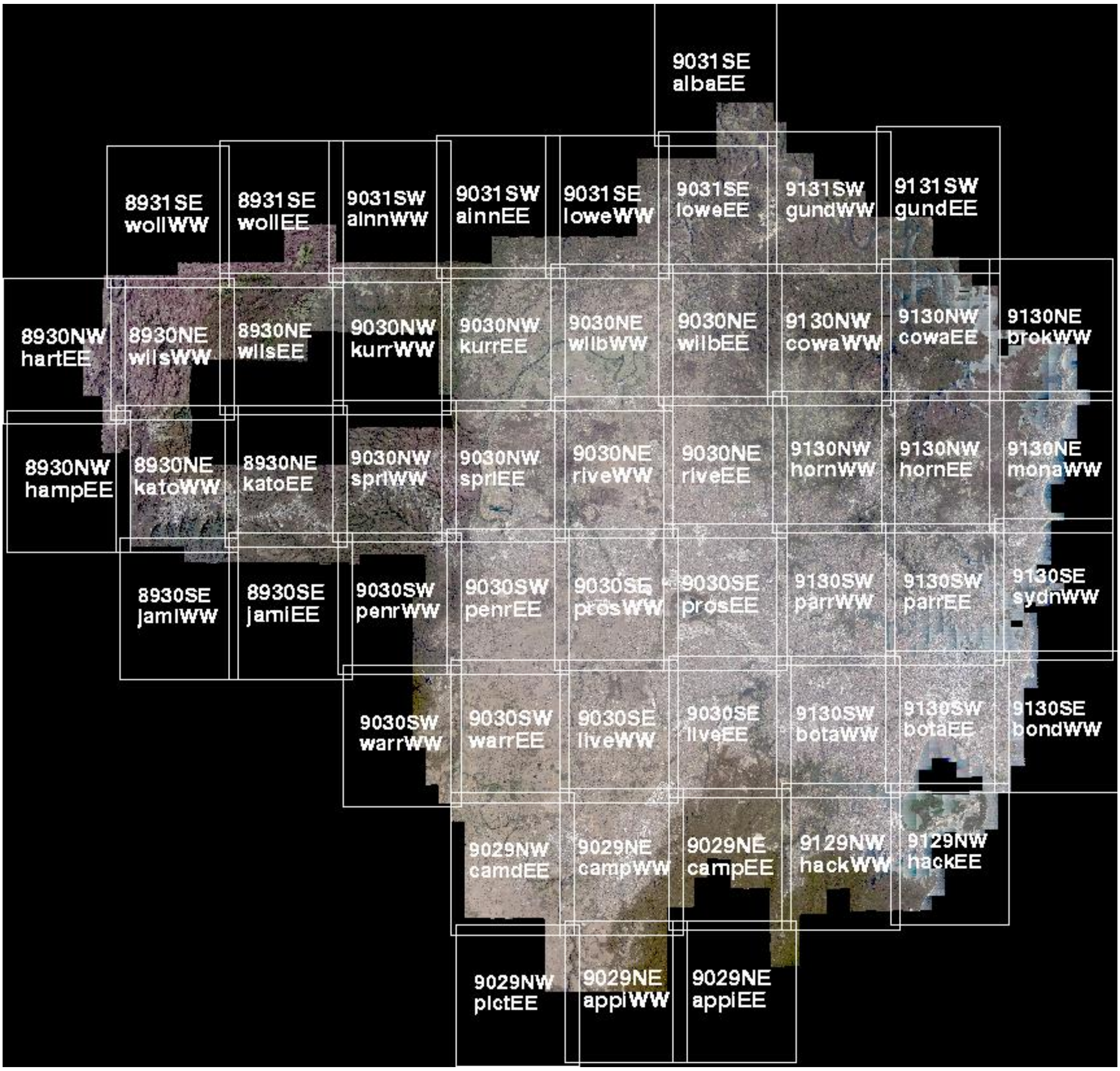


Figure 26 Urban Monitor Sydney map tiles with tile names for year 2014.

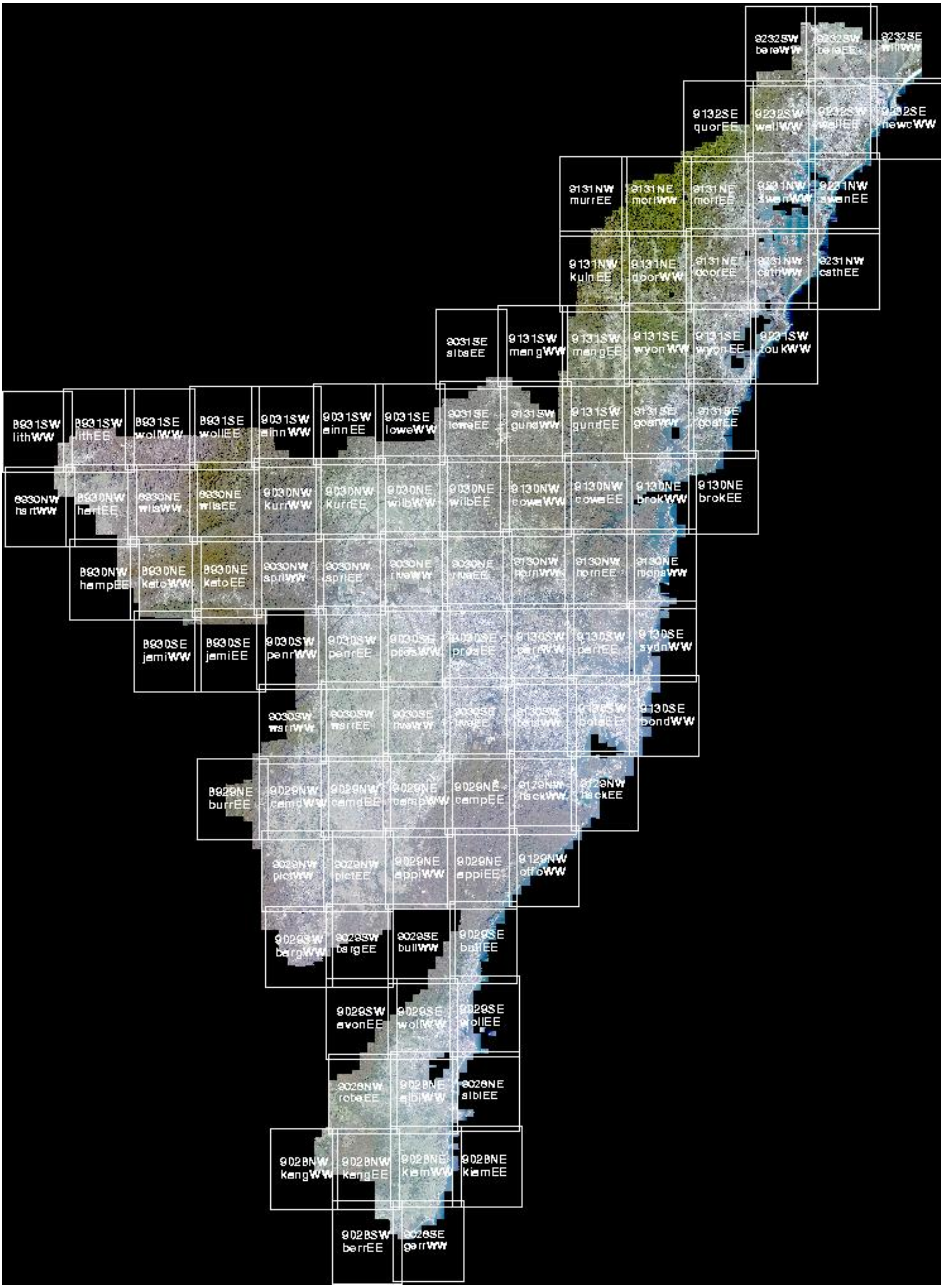


Figure 27 Urban Monitor Sydney map tiles with tile names for year 2016.

Table 3 Urban Monitor (Sydney) 2014 valid map tile extents (name, sizes and coordinates)

Tile Grid (row,col)	Map_ID	Width (Eastings)	Height (Northings)	Top-Left Easting	Top-Left Northing	Bottom-Right Easting	Bottom-Right Northing
06,07	9031SE_albaEE	13000	15000	301500	6319500	314500	6304500
07,02	8931SE_wollWW	13000	15000	243500	6304500	256500	6289500
07,03	8931SE_wollEE	13000	15500	255500	6305000	268500	6289500
07,04	9031SW_ainnWW	13000	15000	267000	6305000	280000	6290000
07,05	9031SW_ainnEE	13000	15000	278500	6305500	291500	6290500
07,06	9031SE_loweWW	13000	15000	290000	6305500	303000	6290500
07,07	9031SE_loweEE	12500	15000	302000	6306000	314500	6291000
07,08	9131SW_gundWW	13000	15000	313500	6306000	326500	6291000
07,09	9131SW_gundEE	13000	15500	325000	6306500	338000	6291000
08,01	8930NW_hartEE	13000	15500	232500	6290500	245500	6275000
08,02	8930NE_wilsWW	13000	15000	244000	6290500	257000	6275500
08,03	8930NE_wilsEE	13000	15000	255500	6291000	268500	6276000
08,04	9030NW_kurrWW	12500	15500	267500	6291500	280000	6276000
08,05	9030NW_kurrEE	13000	15000	279000	6291500	292000	6276500
08,06	9030NE_wilbWW	13000	15500	290500	6292000	303500	6276500
08,07	9030NE_wilbEE	13000	15000	302000	6292000	315000	6277000
08,08	9130NW_cowaWW	13000	15000	313500	6292000	326500	6277000
08,09	9130NW_cowaEE	12500	15000	325500	6292500	338000	6277500
08,10	9130NE_brokWW	13000	15000	337000	6292500	350000	6277500
09,01	8930NW_hampEE	13000	15000	233000	6276500	246000	6261500
09,02	8930NE_katoWW	13000	15500	244500	6277000	257500	6261500
09,03	8930NE_katoEE	13000	15000	256000	6277000	269000	6262000
09,04	9030NW_spriWW	13000	15000	267500	6277500	280500	6262500
09,05	9030NW_spriEE	13000	15000	279000	6277500	292000	6262500
09,06	9030NE_riveWW	12500	15000	291000	6278000	303500	6263000
09,07	9030NE_riveEE	13000	15000	302500	6278000	315500	6263000
09,08	9130NW_hornWW	13000	15000	314000	6278500	327000	6263500
09,09	9130NW_hornEE	13000	15000	325500	6278500	338500	6263500
09,10	9130NE_monaWW	13000	15000	337000	6278500	350000	6263500
10,02	8930SE_jamiWW	12500	15000	245000	6263000	257500	6248000
10,03	8930SE_jamiEE	13000	15500	256500	6263500	269500	6248000
10,04	9030SW_penrWW	13000	15000	268000	6263500	281000	6248500
10,05	9030SW_penrEE	13000	15500	279500	6264000	292500	6248500
10,06	9030SE_prosWW	13000	15000	291000	6264000	304000	6249000
10,07	9030SE_prosEE	13000	15500	302500	6264500	315500	6249000
10,08	9130SW_parrWW	12500	15000	314500	6264500	327000	6249500
10,09	9130SW_parrEE	12500	15000	326000	6264500	338500	6249500
10,10	9130SE_sydnWW	12500	15000	337500	6265000	350000	6250000
11,04	9030SW_warrWW	12500	15000	268500	6249500	281000	6234500
11,05	9030SW_warrEE	12500	15000	280000	6250000	292500	6235000

11,06	9030SE_liveWW	12500	15000	291500	6250000	304000	6235000
11,07	9030SE_liveEE	13000	15000	303000	6250500	316000	6235500
11,08	9130SW_botaWW	13000	15000	314500	6250500	327500	6235500
11,09	9130SW_botaEE	13000	15000	326000	6251000	339000	6236000
11,10	9130SE_bondWW	13000	15000	337500	6251000	350500	6236000
12,05	9029NW_camdEE	13000	15000	280000	6236000	293000	6221000
12,06	9029NE_campWW	13000	15500	291500	6236500	304500	6221000
12,07	9029NE_campEE	13000	15000	303000	6236500	316000	6221500
12,08	9129NW_hackWW	12500	15500	315000	6237000	327500	6221500
12,09	9129NW_hackEE	12500	15000	326500	6237000	339000	6222000
13,05	9029NW_pictEE	13000	15000	280500	6222000	293500	6207000
13,06	9029NE_appiWW	13000	15000	292000	6222500	305000	6207500
13,07	9029NE_appiEE	13000	15000	303500	6222500	316500	6207500

Table 4 Urban Monitor (Sydney) 2016 valid map tile extents (name, sizes and coordinates)

Tile Grid (row,col)	Map_ID	Width (Eastings)	Height (Northings)	Top-Left Easting	Top-Left Northing	Bottom-Right Easting	Bottom-Right Northing
02,12	9232SW_bereWW	13000	15000	359000	6376000	372000	6361000
02,13	9232SW_bereEE	13000	15000	370500	6376000	383500	6361000
02,14	9232SE_willWW	13000	15000	382500	6376500	395500	6361500
03,11	9132SE_quorEE	13000	15000	347500	6362000	360500	6347000
03,12	9232SW_wallWW	13000	15000	359000	6362000	372000	6347000
03,13	9232SW_wallEE	12500	15000	371000	6362500	383500	6347500
03,14	9232SE_newcWW	13000	15000	382500	6362500	395500	6347500
04,09	9131NW_murrEE	12500	15000	324500	6348000	337000	6333000
04,10	9131NE_moriWW	13000	15000	336000	6348000	349000	6333000
04,11	9131NE_moriEE	13000	15000	347500	6348000	360500	6333000
04,12	9231NW_swanWW	12500	15000	359500	6348500	372000	6333500
04,13	9231NW_swanEE	13000	15000	371000	6348500	384000	6333500
05,09	9131NW_kulnEE	13000	15000	324500	6334000	337500	6319000
05,10	9131NE_doorWW	13000	15000	336000	6334000	349000	6319000
05,11	9131NE_doorEE	13000	15000	348000	6334500	361000	6319500
05,12	9231NW_cathWW	13000	15000	359500	6334500	372500	6319500
05,13	9231NW_cathEE	13000	15000	371000	6334500	384000	6319500
06,07	9031SE_albaEE	13000	15000	301500	6319500	314500	6304500
06,08	9131SW_mangWW	13000	15000	313000	6320000	326000	6305000
06,09	9131SW_mangEE	12500	15000	325000	6320000	337500	6305000
06,10	9131SE_wyonWW	13000	15000	336500	6320500	349500	6305500
06,11	9131SE_wyonEE	13000	15000	348000	6320500	361000	6305500
06,12	9231SW_toukWW	12500	15000	360000	6320500	372500	6305500
07,00	8931SW_lithWW	13000	15000	220500	6304000	233500	6289000
07,01	8931SW_lithEE	13000	15500	232000	6304500	245000	6289000
07,02	8931SE_wollWW	13000	15000	243500	6304500	256500	6289500
07,03	8931SE_wollEE	13000	15500	255500	6305000	268500	6289500
07,04	9031SW_ainnWW	13000	15000	267000	6305000	280000	6290000

07,05	9031SW_ainnEE	13000	15000	278500	6305500	291500	6290500
07,06	9031SE_loweWW	13000	15000	290000	6305500	303000	6290500
07,07	9031SE_loweEE	12500	15000	302000	6306000	314500	6291000
07,08	9131SW_gundWW	13000	15000	313500	6306000	326500	6291000
07,09	9131SW_gundEE	13000	15500	325000	6306500	338000	6291000
07,10	9131SE_gosfWW	13000	15000	336500	6306500	349500	6291500
07,11	9131SE_gosfEE	12500	15000	348500	6306500	361000	6291500
08,00	8930NW_hartWW	13000	15000	221000	6290000	234000	6275000
08,01	8930NW_hartEE	13000	15500	232500	6290500	245500	6275000
08,02	8930NE_wilsWW	13000	15000	244000	6290500	257000	6275500
08,03	8930NE_wilsEE	13000	15000	255500	6291000	268500	6276000
08,04	9030NW_kurrWW	12500	15500	267500	6291500	280000	6276000
08,05	9030NW_kurrEE	13000	15000	279000	6291500	292000	6276500
08,06	9030NE_wilbWW	13000	15500	290500	6292000	303500	6276500
08,07	9030NE_wilbEE	13000	15000	302000	6292000	315000	6277000
08,08	9130NW_cowaWW	13000	15000	313500	6292000	326500	6277000
08,09	9130NW_cowaEE	12500	15000	325500	6292500	338000	6277500
08,10	9130NE_brokWW	13000	15000	337000	6292500	350000	6277500
08,11	9130NE_brokEE	13000	15500	348500	6293000	361500	6277500
09,01	8930NW_hampEE	13000	15000	233000	6276500	246000	6261500
09,02	8930NE_katoWW	13000	15500	244500	6277000	257500	6261500
09,03	8930NE_katoEE	13000	15000	256000	6277000	269000	6262000
09,04	9030NW_spriWW	13000	15000	267500	6277500	280500	6262500
09,05	9030NW_spriEE	13000	15000	279000	6277500	292000	6262500
09,06	9030NE_riveWW	12500	15000	291000	6278000	303500	6263000
09,07	9030NE_riveEE	13000	15000	302500	6278000	315500	6263000
09,08	9130NW_hornWW	13000	15000	314000	6278500	327000	6263500
09,09	9130NW_hornEE	13000	15000	325500	6278500	338500	6263500
09,10	9130NE_monaWW	13000	15000	337000	6278500	350000	6263500
10,02	8930SE_jamiWW	12500	15000	245000	6263000	257500	6248000
10,03	8930SE_jamiEE	13000	15500	256500	6263500	269500	6248000
10,04	9030SW_penrWW	13000	15000	268000	6263500	281000	6248500
10,05	9030SW_penrEE	13000	15500	279500	6264000	292500	6248500
10,06	9030SE_prosWW	13000	15000	291000	6264000	304000	6249000
10,07	9030SE_prosEE	13000	15500	302500	6264500	315500	6249000
10,08	9130SW_parrWW	12500	15000	314500	6264500	327000	6249500
10,09	9130SW_parrEE	12500	15000	326000	6264500	338500	6249500
10,10	9130SE_sydnWW	12500	15000	337500	6265000	350000	6250000
11,04	9030SW_warrWW	12500	15000	268500	6249500	281000	6234500
11,05	9030SW_warrEE	12500	15000	280000	6250000	292500	6235000
11,06	9030SE_liveWW	12500	15000	291500	6250000	304000	6235000
11,07	9030SE_liveEE	13000	15000	303000	6250500	316000	6235500
11,08	9130SW_botaWW	13000	15000	314500	6250500	327500	6235500
11,09	9130SW_botaEE	13000	15000	326000	6251000	339000	6236000
11,10	9130SE_bondWW	13000	15000	337500	6251000	350500	6236000
12,03	8929NE_burrEE	13000	15000	257000	6235500	270000	6220500

12,04	9029NW_camdWW	13000	15500	268500	6236000	281500	6220500
12,05	9029NW_camdEE	13000	15000	280000	6236000	293000	6221000
12,06	9029NE_campWW	13000	15500	291500	6236500	304500	6221000
12,07	9029NE_campEE	13000	15000	303000	6236500	316000	6221500
12,08	9129NW_hackWW	12500	15500	315000	6237000	327500	6221500
12,09	9129NW_hackEE	12500	15000	326500	6237000	339000	6222000
13,04	9029NW_pictWW	13000	15000	269000	6222000	282000	6207000
13,05	9029NW_pictEE	13000	15000	280500	6222000	293500	6207000
13,06	9029NE_appiWW	13000	15000	292000	6222500	305000	6207500
13,07	9029NE_appiEE	13000	15000	303500	6222500	316500	6207500
13,08	9129NW_otfoWW	13000	15000	315000	6223000	328000	6208000
14,04	9029SW_bargWW	12500	15000	269500	6208000	282000	6193000
14,05	9029SW_bargEE	12500	15500	281000	6208500	293500	6193000
14,06	9029SE_bullWW	12500	15000	292500	6208500	305000	6193500
14,07	9029SE_bullEE	12500	15500	304000	6209000	316500	6193500
15,05	9029SW_avonEE	13000	15000	281000	6194500	294000	6179500
15,06	9029SE_wollWW	13000	15000	292500	6194500	305500	6179500
15,07	9029SE_wollEE	13000	15000	304000	6195000	317000	6180000
16,05	9028NW_robeEE	12500	15000	281500	6180500	294000	6165500
16,06	9028NE_albiWW	12500	15500	293000	6181000	305500	6165500
16,07	9028NE_albiEE	12500	15000	304500	6181000	317000	6166000
17,04	9028NW_kangWW	12500	15000	270500	6166500	283000	6151500
17,05	9028NW_kangEE	12500	15000	282000	6166500	294500	6151500
17,06	9028NE_kiamWW	13000	15000	293000	6167000	306000	6152000
17,07	9028NE_kiamEE	13000	15000	304500	6167000	317500	6152000
18,05	9028SW_berrEE	13000	15500	282000	6153000	295000	6137500
18,06	9028SE_gerrWW	13000	15000	293500	6153000	306500	6138000

The Map_ID is formed in the following way: the first part of Map_ID is the 1:50,000 map name which includes 4-digit identification number of the 1:100,000 map (national standards, see Figure 28) and the 1:50,000 map spatial relationship (NW, NE, SW, SE) within the 1:100,000 map extents; since in NSW, two north or two south 1:25,000 maps within a 1:50,000 map share the same name, therefore the second part of Map_ID is the 1:25,000 map name which uses the four-letter from the name of two north 1:25,000 maps in the current 1:50,000 map extents as the key name, then followed by the spatial relationship (WW means the west 1:25,000 map, EE means the east 1:25,000 map) to identify which 1:25,000 map. For example, 8932NW_taloWW is the north-west 1:25,000 map within the 1:50,000 map of 8932NW while 8932NW_growEE is the south-east 1:25,000 map within the 1:50,000 map of 8932NW.

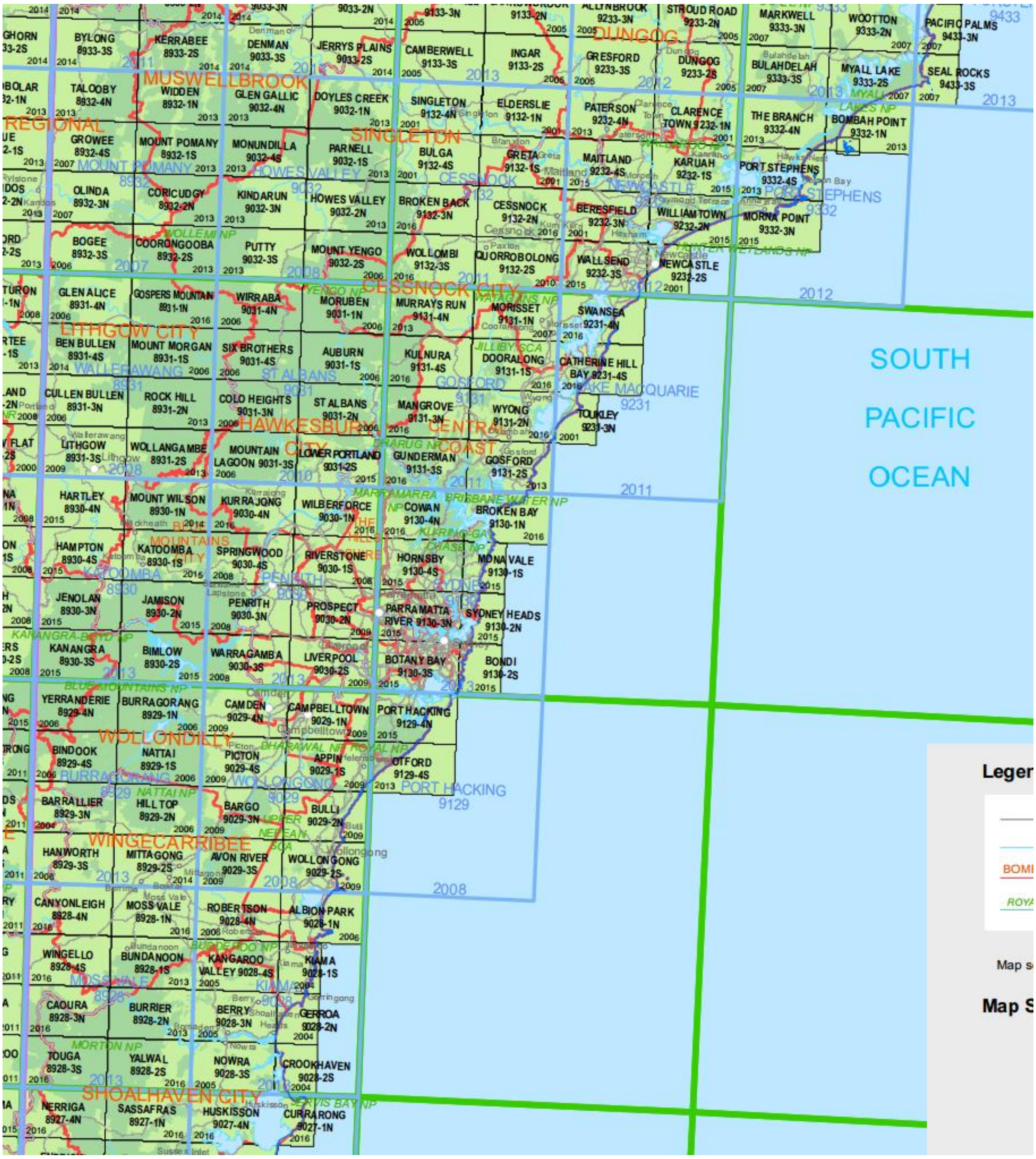


Figure 28 Urban Monitor Sydney region covered in New South Wales topographic map catalogue (2017). Reference: https://nla.gov.au/nla.obj-611201730/view

4.2 Map sheet Extents

Currently raster binary products are formed and stored in BIL format, and each BIL file is accompanied by an ERMapper raster header file (with extension .ers), and some vector data are formed and stored in ERMapper vector format (with extension .erv). The following basic naming conversion is applied for Urban Monitor products (letters are case insensitive):

year_mon_UM_snrID_mapsID_nameID_ geoid_mproj_xxx_yyy_client_timeTag_state

where

- year: 4 digits for the year the majority images were captured
- mon: 3 letters for the month the majority images were captured
- UM: 2 letters to identify the products were derived using CSIRO Urban Monitor technology
- snrID: data capturing sensor ID. 3 letters followed by 2 digits, e.g. ucd00, ads40, ads80 etc.
- mapsID: 4 digits of the 1:100,000 map ID followed by two letters of quadrant ID, e.g. 2033NE
- nameID: 4 letters of the north-eastern 1:25,000 map name followed by two letters of quadrant ID, e.g. botaEE
- geoid: 5 letters to specify the geoids e.g. gda94
- mproj: 5 letters to map projection e.g. mga50
- xxx: 3 letters to name the nature of the product, e.g. dsm, msp, dem, gem, nsm, msk etc.
- yyy: 3 letters to specify special processing applied e.g. non-editing (raw), radiometric calibration (cal), terrain illumination correction (ter) etc.
- client: 5 letters used to indicate the client/custom of this product
- timeTag: 10 digits to stamp the date/hour the file was produced, e.g. 2012053110
- state: 5 letters to specify the production state/version e.g. ver01, final etc.

Current available xxx options are (not limited):

- dsm: digital surface model. 32bit signed integer, unit is in millimetre
- dom: multispectral orthorectified mosaic. 16bit unsigned integer
- gem: ground elevation model. 32bit signed integer, unit is in millimetre
- nsm: normalised surface model. 32bit signed integer, unit is in millimetre
- msk: mask layer. 8bit unsigned integer. The type of mask is specified in yyy or its corresponding .hst file
- veg: a veg/not-veg Unsigned8BitInteger file showing vegetation as 1
- vht: heights of vegetation, unit is in millimetre
- vin: vegetation index (mostly ndvi) in single floating data type
- grs: ground height vegetation (grass). 2 class data. (1=vegetation close to the ground, 0=everything else)
- tre: vegetation above ground 2 class data. (1=vegetation above the ground, 0=everything else)

Current available yyy options are (not limited):

- raw: non-editing
- cal: radiometric calibration
- wtr: for water mask
- edt: for data that has been manually edited after the entire tile has been generated. For example fixing the ndsm would mean a *dsm_edt* file created, then generating the

vegetation heights map would give a *vht_raw* file because veg heights itself hasn't been manually corrected.

File name samples:

- Digital Surface Model (without editing):
2016_jan_UM_ucd16_9130SW_botaEE_gda94_mga56_dsm_raw_OEHAU_2018060123_ver01

- Multispectral image (BRDF calibrated):
2016_jan_UM_ucd16_9130SW_botaEE_gda94_mga56_dom_cal_OEHAU_2018060123_ver01

- Ground elevation model (after manual editing):
2016_jan_UM_ucd16_9130SW_botaEE_gda94_mga56_gem_edt_OEHAU_2018060123_ver01

- Ground elevation model (mask):
2016_jan_UM_ucd16_9130SW_botaEE_gda94_mga56_gem_msk_OEHAU_2018060123_ver01

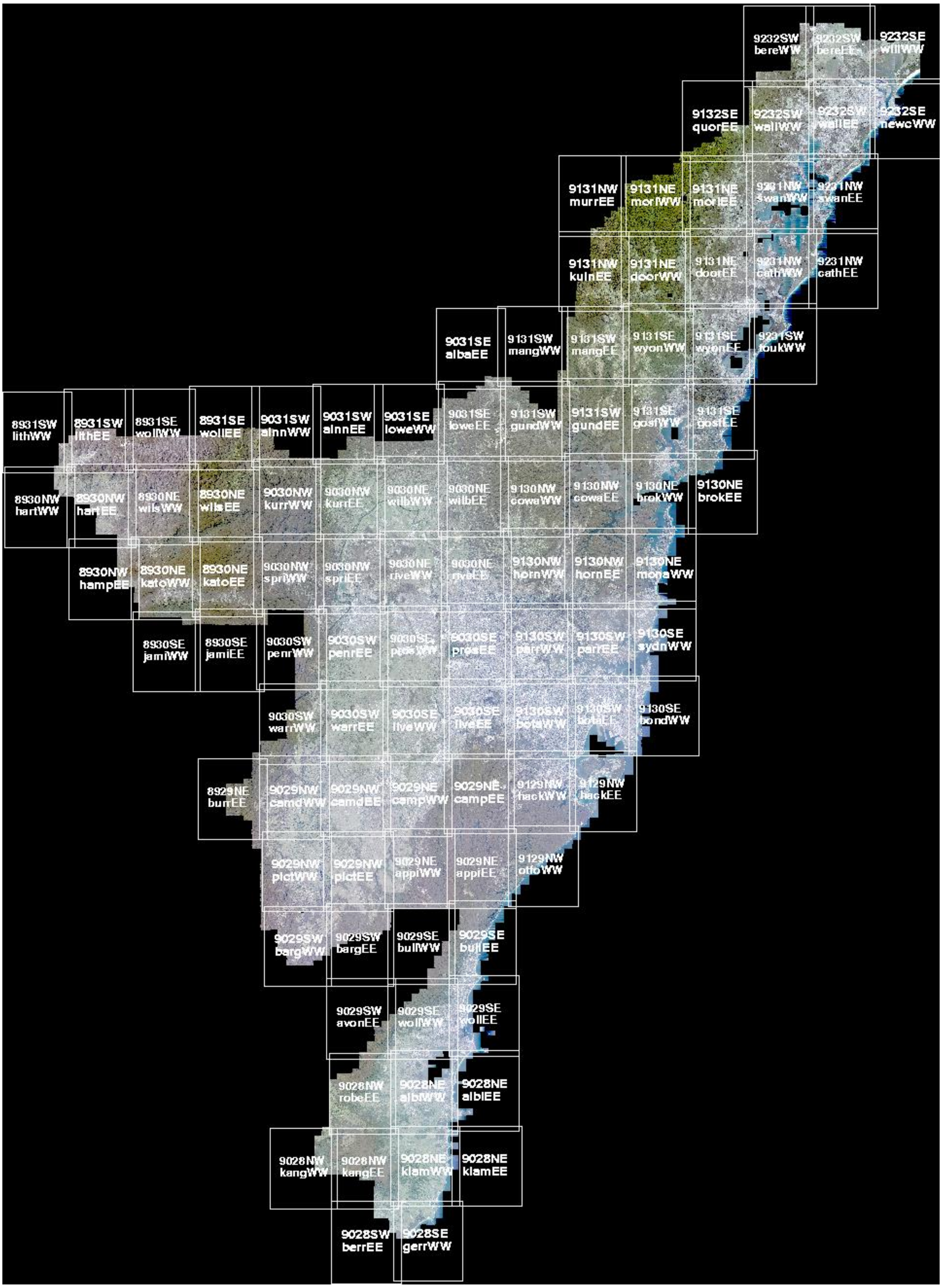
  This is an Unsigned8BitInteger file showing edited area as 1. LiDaR DEM has been used to edit the current GEM where there is thick vegetation cover. The associated products – gem, nsm, vht, grs and tre are marked with (v02) at the end of the filename.

  Note that map sheets belonging to the Blue Mountains have not been edited as no LiDaR DEM was available in this area.

4.3 Format of Products

The raster products are formed and stored in band-interleaved-by-line format (BIL), and each BIL file is accompanied by an ERMapper raster header file (with extension .ers). The ground sampling distance (GSD) of all the raster products is 0.2m. The vector products are formed and stored in a text file in ERMapper format, each accompanied by an ERMapper vector header (with extension .erv)

Appendix A nlarged Map of Sheet Extents



Glossary

DSM	Digital Surface Model
GEM	Ground Elevation Model

References

Caccetta, P., Collings, S., Devereux, A., Hingee, K., McFarlane, D., Traylen, A., Wu, X. and Zhou, Z.S., 2016. Monitoring land surface and cover in urban and peri-urban environments using digital aerial photography. International Journal of Digital Earth,9(5), pp.457-475.
DOI: 10.1080/17538947.2015.1046510.

Collings, S. and Caccetta, P. (2013) Radiometric calibration of very large digital aerial frame mosaics, International Journal of Image and Data Fusion, 4:3, 214-229,
DOI: 10.1080/19479832.2012.760656

Devereux D and Caccetta PA (2017) Estimation of Land Surface Temperature and Urban Heat Island effect for Australian urban centres. CSIRO Data61, Australia. Report EP173542.

Leberl, F. and Gruber, M. (2003). “Flying the New Large Format Digital Aerial Camera Ultracam,” in Photogramm. Week, D. Fritsch, Ed. Heidelberg, Germany: Wichmann Verlag, pp. 67–76.

CONTACT US

t 1300 363 400
+61 3 9545 2176
e csiroenquiries@csiro.au
w www.data61.csiro.au

AT CSIRO WE SHAPE THE FUTURE

We do this by using science and technology to solve real issues. Our research makes a difference to industry, people and the planet.

FOR FURTHER INFORMATION

Dr. Peter Caccetta
Senior Principal Research Scientist
t +61 8 9333 6188
e Peter.Cacccetta@CSIRO.au
w www.data61.csiro.au

Dr. Joanne Chia
Research Scientist
t +61 8 9333 6138
e Joanne.Chia@CSIRO.au
w www.data61.csiro.au