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The Creation Of High Resolution Bathymetry Grids for Cocos (Keeling) Island

Richard Mleczko and Stephen Sagar

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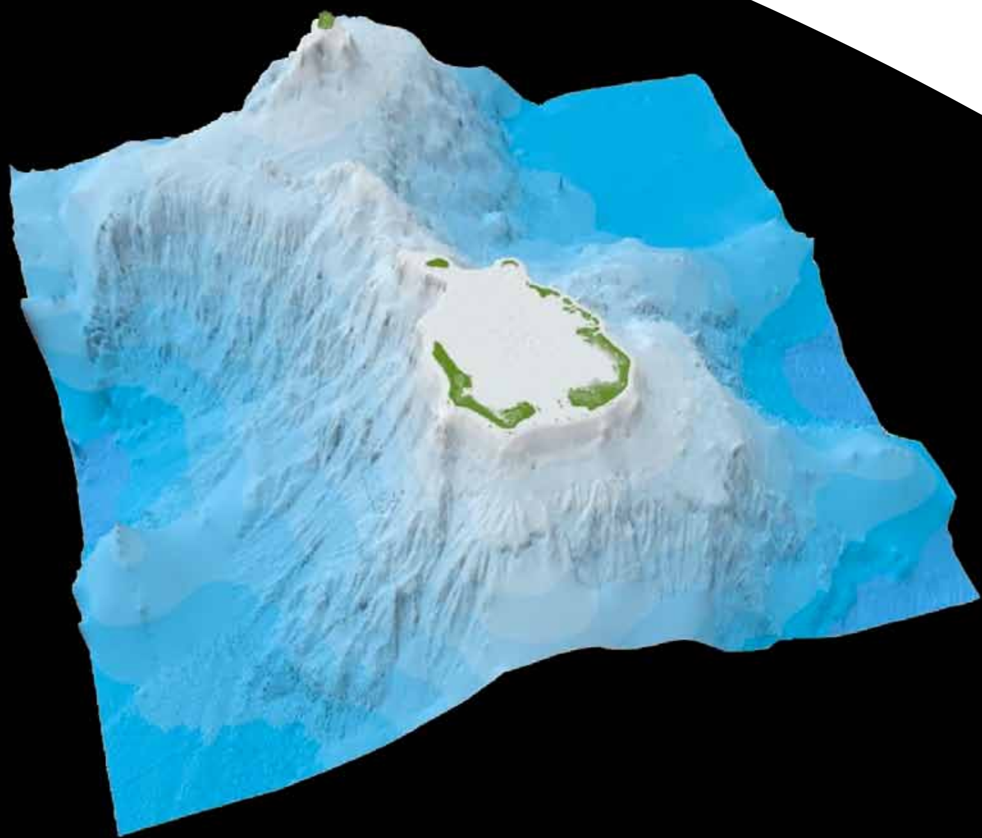

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

The Creation of High Resolution Bathymetry Grids for Cocos (Keeling) Island

GEOSCIENCE AUSTRALIA
RECORD 2010/38

by

Richard Mleczko and Stephen Sagar

Australian Government
Geoscience Australia

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Executive Summary

Cocos (Keeling) Island is located approximately 3,685 km almost due west of Darwin. It is a mid-ocean atoll with a coral reef, and a very shallow (1 – 20 m) shelf surrounds the island. Bathymetry data are required in this area to help identify major seabed processes and habitats. The data are also required to enable modelling of tsunami as they interact with the shelf around the island and the coast.

This report describes the methodology employed in creating detailed bathymetric grids of the Cocos (Keeling) Island region. It covers data collation, quality control and gridding. Descriptions are provided for each dataset employed, the methods used to integrate the different datasets and the attributes of the new bathymetric models.

Four new bathymetric grids are presented, including grids that integrate bathymetry with the island's topography.

1. Introduction

Cocos (Keeling) Island (12^0 07' S, 96^0 53' E) is an Australian territory with a population of over 500 people. It is a raised atoll which lies on oceanic crust approximately 2950 km northwest of Perth and 1000 km southwest of Sumatra. There are 27 coral islands in the group with an area of 14 km^2. Cocos (Keeling) Island is adjacent to a tsunami-genic zone and therefore the first part of Australia to be affected by any tsunami, making it a priority to hazard modellers.

The Cocos (Keeling) Islands including North Keeling Island are of significant importance to the scientific community with respect to coral reef development (Woodroffe, 1994) and the only coral atoll visited by Charles Darwin. It has been the subject of studies such as sea level rise (Woodroffe, 1993), storm surges (GHD, 2001), conservation (Brewer, 2009), groundwater (Jacobson, 1976), magnetism (Finlayson, 1970) and geology (Jongsma, 1976). It is noted in Brewer (2009) that there is a paucity of bathymetric data.

The Geospatial and Earth Monitoring Division (GEMD) tsunami modelling team investigated different bathymetry grids (such as the ones mentioned in this document) and tested them in tsunami modelling, (Burbidge 2007). Most grids did not reproduce the correct frequency content found in real Cocos (Keeling) Island tide gauge records. Hydrodynamic equations used in tsunami modelling in the far field are insensitive to small changes in the earthquake source model, however, small changes in the bathymetry of the shelf and nearshore can have a dramatic effect on model outputs. Therefore, accurate, detailed bathymetric data are essential. The collation of all available bathymetric data for the island and generation of a detailed digital terrain model (DTM) will enable improved modelling of tsunami interaction with the island's shelf and coast.

The grids presented here complement the GIS of Cocos (Keeling) Island created by the Onshore Energy and Minerals Division (OEMD), see Porritt (2006). This GIS contains very detailed on-shore environmental data but no bathymetry. Over the years people have sought out bathymetry from this GIS and have not been able to extract any. The work done here will now make it possible to add bathymetry to this GIS.

This report provides a detailed description of the diverse datasets that were collated to produce the new bathymetric grids. The grids cover the nearshore and shallow shelf that surrounds the island, the Cocos (Keeling) Island raised atoll and the broader surrounding region including North Keeling Island. Maps of data distribution and three dimensional Digital Terrain Models (DTMs) are provided for each of these areas.

2. Existing Bathymetry Grids

WHAT IS AVAILABLE?

There are many publicly available bathymetry grids (see Marks et al 2006) but none dedicated to the Cocos (Keeling) Island region. However one dedicated Cocos (Keeling) Island grid which was not in the public domain was found. It was created by Systems Engineering Australia (SEA) under contract to Gutteridge Haskins and Davy Pty. Ltd. (GHD) and was commissioned by the Department of Transport and Regional Services (DoTaRS) for a storm surge study in 2001. It is shown in Figure 1 and more details can be found in Harper (2001) and GHD (2001). It shows many features that are lacking from the publicly available bathymetry grids but which are present in the final grids created in this work. It is based on chart data, survey data, satellite images, reef profiles and aerial photography, its resolution is 80 metres.

Subsets of four global or large regional grids are discussed here focusing on Cocos (Keeling) Island. All views in the figures are approximately 96^{o} to 98^{o} E and 11^{o} to 13 ^{o} S and have a vertical exaggeration of 6 times.

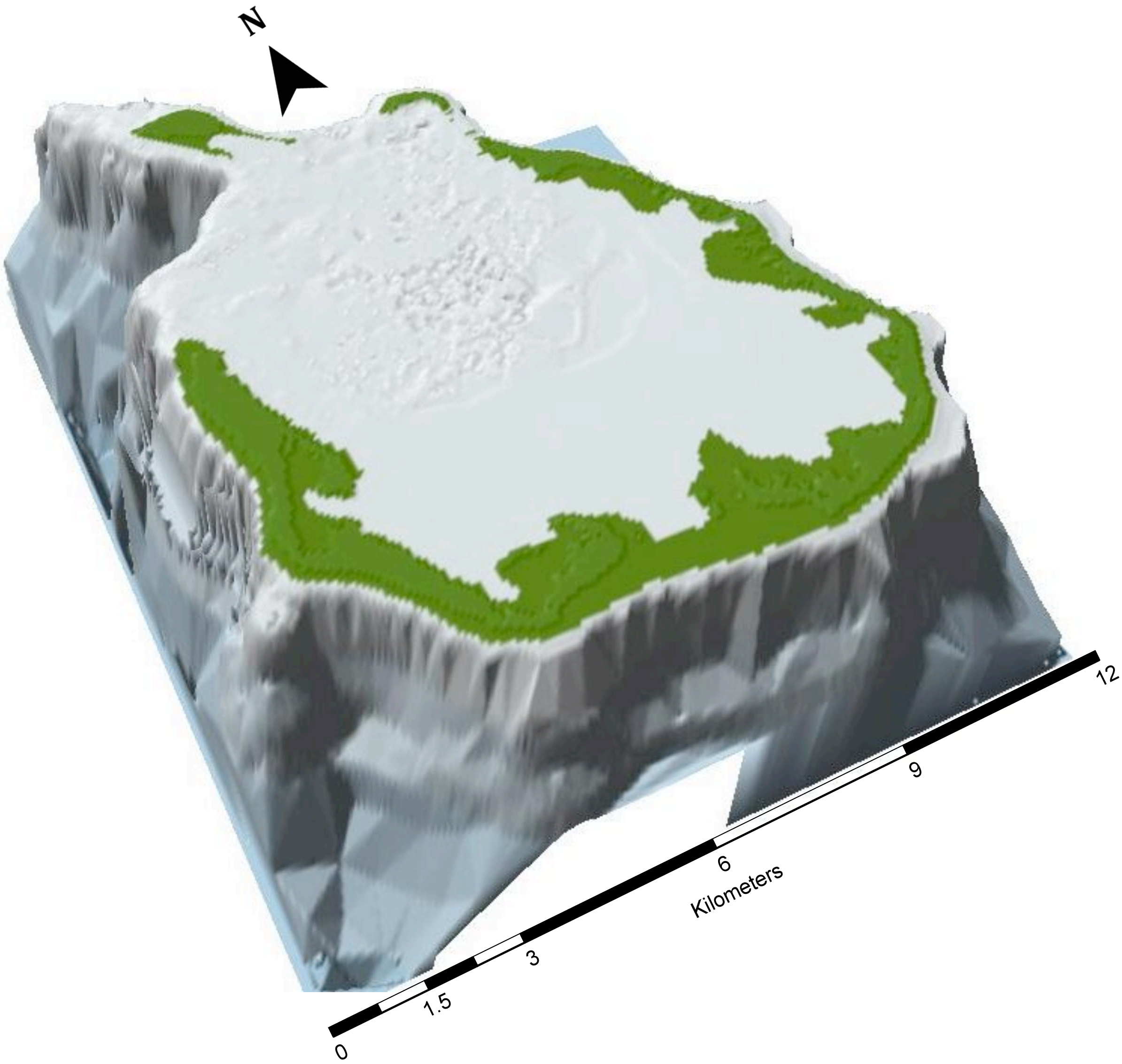


Figure 1: *The early Cocos (Keeling) Island GHD grid from 2001.*

The Australian Bathymetry and Topography grid

In 2005 Geoscience Australia (GA) released its 250 metre (9 sec of arc) grid of the Australian region. The grid was based on limited data sets and chart data from the Australian Hydrographic Service (AHS) was not included. A full explanation of the data sets and the construction of the grid can be found in Webster et al (2005). The 2009 GA grid (Whiteway, 2009) is not compared here as the grids from this work went into that grid. An extract of the model that covers the Cocos (Keeling) Island region is shown in Figure 2.

Features of the Geoscience Australia 250 m grid for the Cocos (Keeling) Island region are:

- There is an erroneous rise to the northwest of the island.
- There is poor representation of the land.
- There is no land for North Keeling Island.

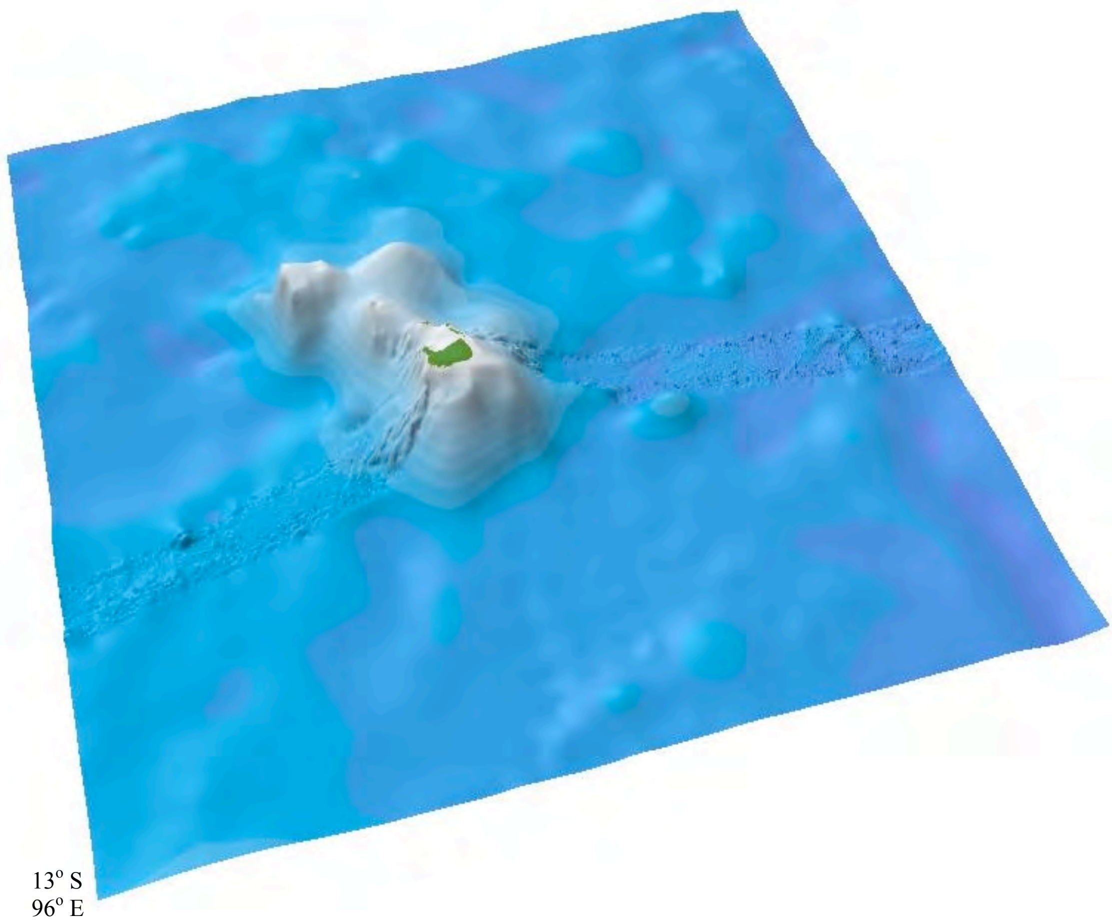


Figure 2: *The region around Cocos (Keeling) Island as represented by the GA Australian Bathymetry and Topography 9 second of arc grid 2005 (position markers are approximate only).*

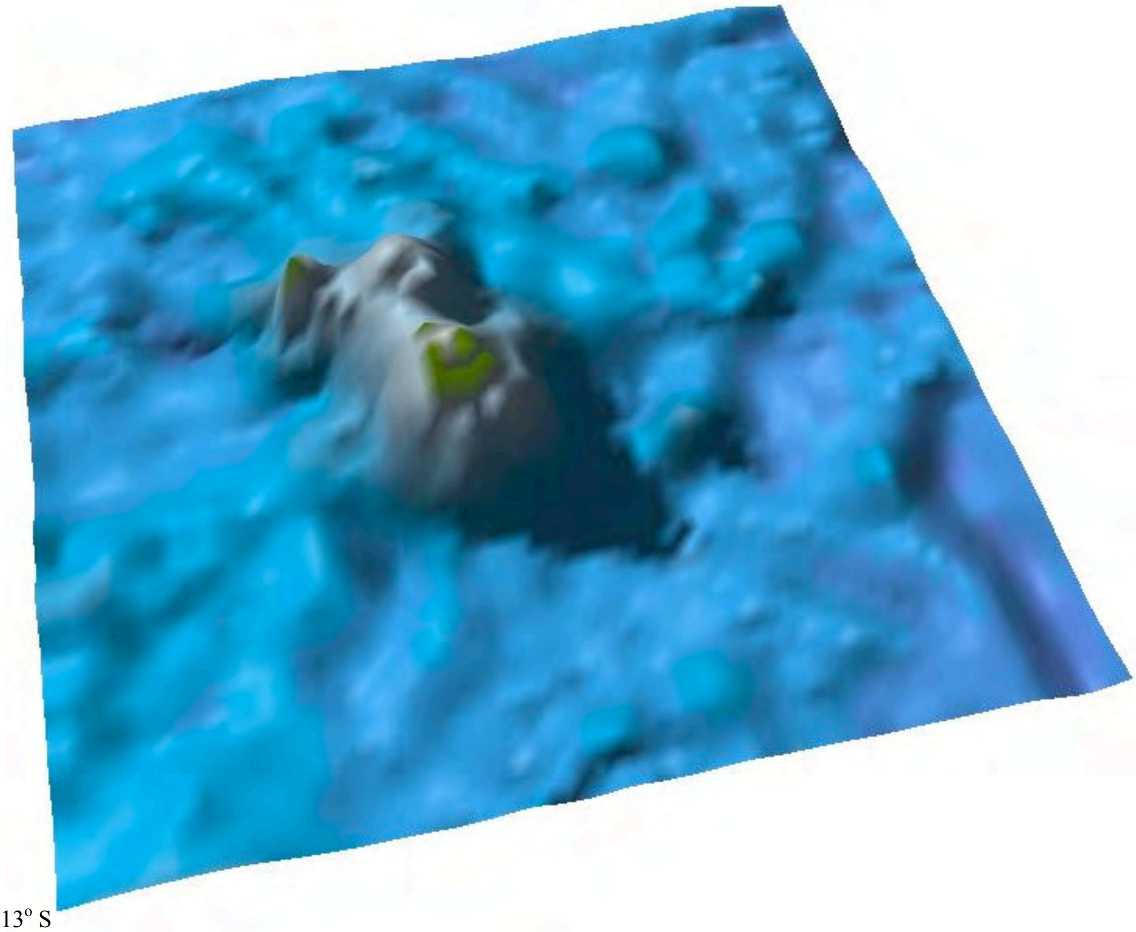
Digital Bathymetry Database 2 minute (DBDB2) grid

The DBDB2 grid is a 2 minute of arc global bathymetry and topography data grid. It was developed by the US Naval Research Laboratory (NRL) and is based on the earlier DBDB5. Global topography from satellite altimetry and ship depth soundings were used in deep water as well as data from GA's 2002 Australian Bathymetry and Topography grid. More information on the construction of this global grid can be found at: http://www7320.nrlssc.navy.mil/DBDB2_WWW/. An extract of the model that covers the Cocos (Keeling) Island region is shown in Figure 3.

Features of the DBDB2 model for the Cocos (Keeling) Island region are:

- There is poor representation of the land.
- North Keeling Island is in the wrong location probably due to the use of the GMT (GMT, 2010) coastline data which is 1 minute too far west.
- There are numerous features on the seafloor.

11° S
98° E



13° S
96° E

Figure 3: *The region around Cocos (Keeling) Island as represented by the DBDB2 2 minute of arc grid (position markers are approximate only).*

Earth Topography 1 minute (ETOPO1) grid

The ETOPO1 grid is a 1 minute of arc global bathymetry and topography data grid. Data for this grid are derived from sea-surface altimetry measurements, ocean soundings, Space Shuttle Radar Topography Mission 30 minute elevation data (SRTM30) and the 30 minute Global Topography data set (GTOPO30). An extract of the model that covers the Cocos (Keeling) Island region is shown in Figure 4. A full description (http://www.ngdc.noaa.gov/mgg/global/etopo1sources.html) of the grid can be found at the link.

This data set is often used to fill in grids where data are missing rather than to interpolate over data gaps. Previous grids at GA have used this methodology. It was found in this work that some of the features in the ETOPO1 grid are not supported by survey data held at GA.

Features of the ETOPO1 model for the Cocos (Keeling) Island region are:

- There is poor representation of the land.
- North Keeling Island is in the correct location, but the wrong shape.
- There are numerous features on the seafloor.

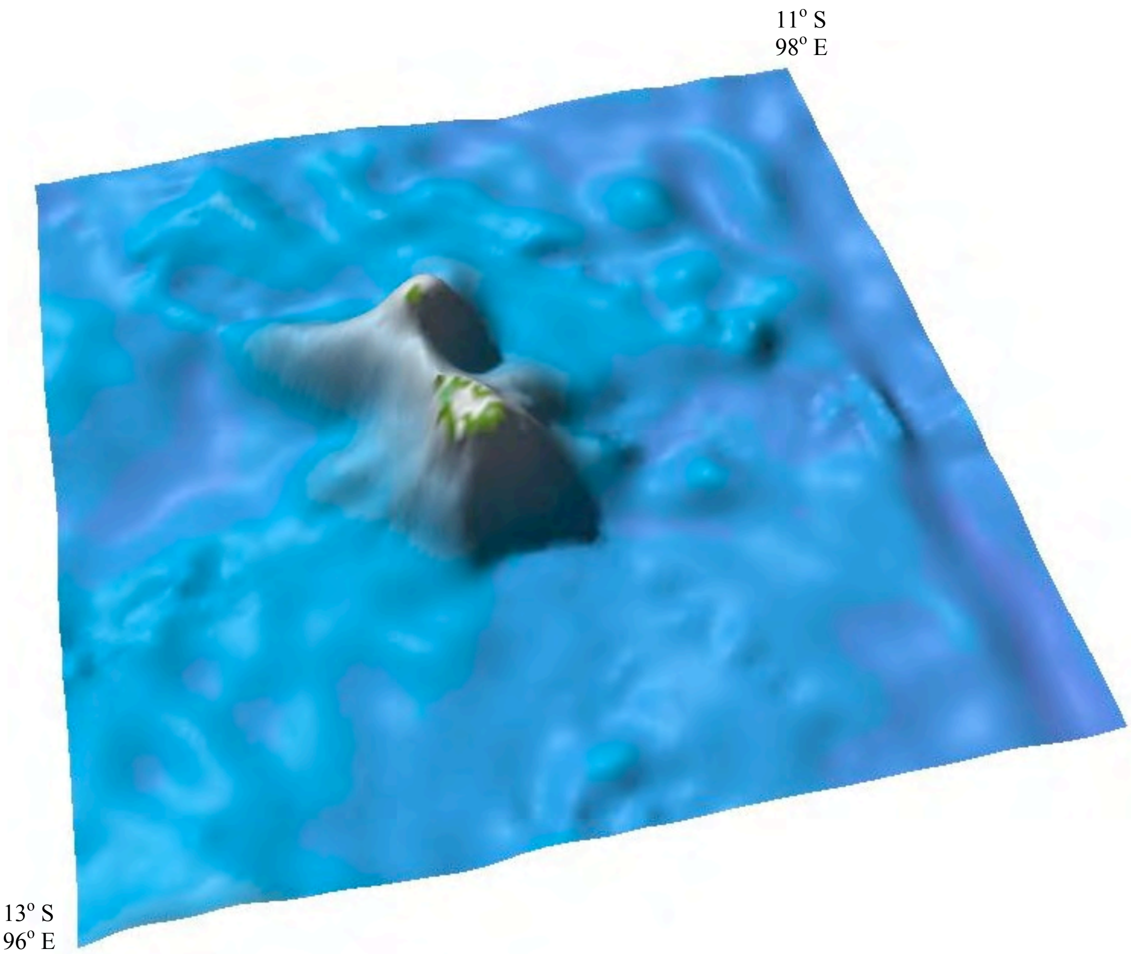


Figure 4: *The region around Cocos (Keeling) Island as represented by the ETOPO 1 minute of arc grid (position markers are approximate only).*

General Bathymetric Chart of the Oceans (GEBCO) grid

The GEBCO grid is a 1 minute of arc global bathymetry and topography data grid. GEBCO is based on the most recent set of contours contained within the GEBCO Digital Atlas. More information on the construction of this global grid and the GEBCO Digital Atlas can be found at http://www.gebco.net/data_and_products/gridded_bathymetry_data/. An extract of the model that covers the Cocos Island region is shown in Figure 5.

Features of the GEBCO model for the Cocos (Keeling) Island region are:

- There is poor representation of the land.
- There is no land for North Keeling Island.
- There are numerous features on the seafloor.

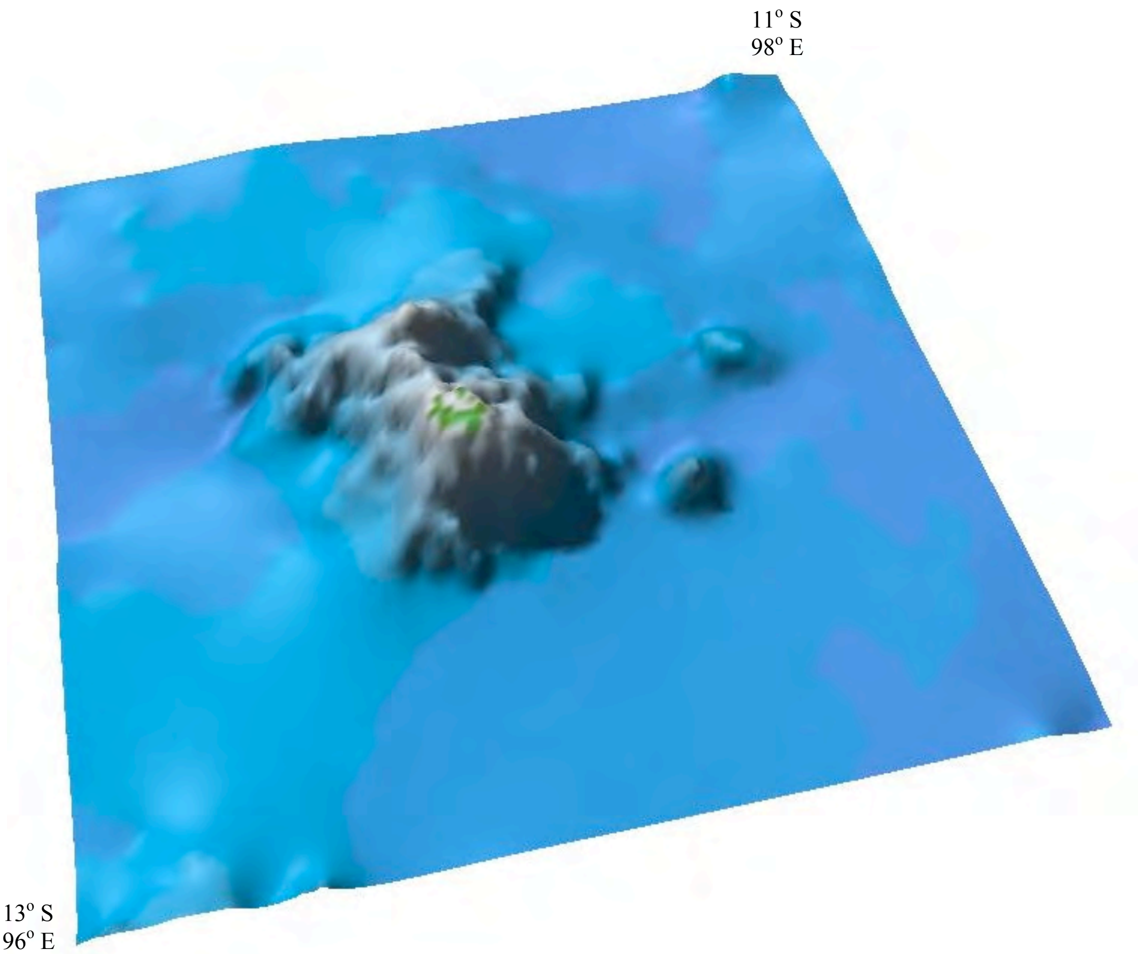


Figure 5: *The region around Cocos (Keeling) Island as represented by the GEBCO 1 minute of arc grid (position markers are approximate only).*

COMPARISON OF THE FOUR GRIDS

The Cocos (Keeling) Island region in the Indian Ocean as represented by the global and Australian bathymetry grids are shown in Figure 6.

Major differences in the representation of the Cocos Island region by the four datasets include:

- The number of features on the sea floor differs.
- The shape and size of the rise differs greatly.
- The shape and size of the land differs greatly.

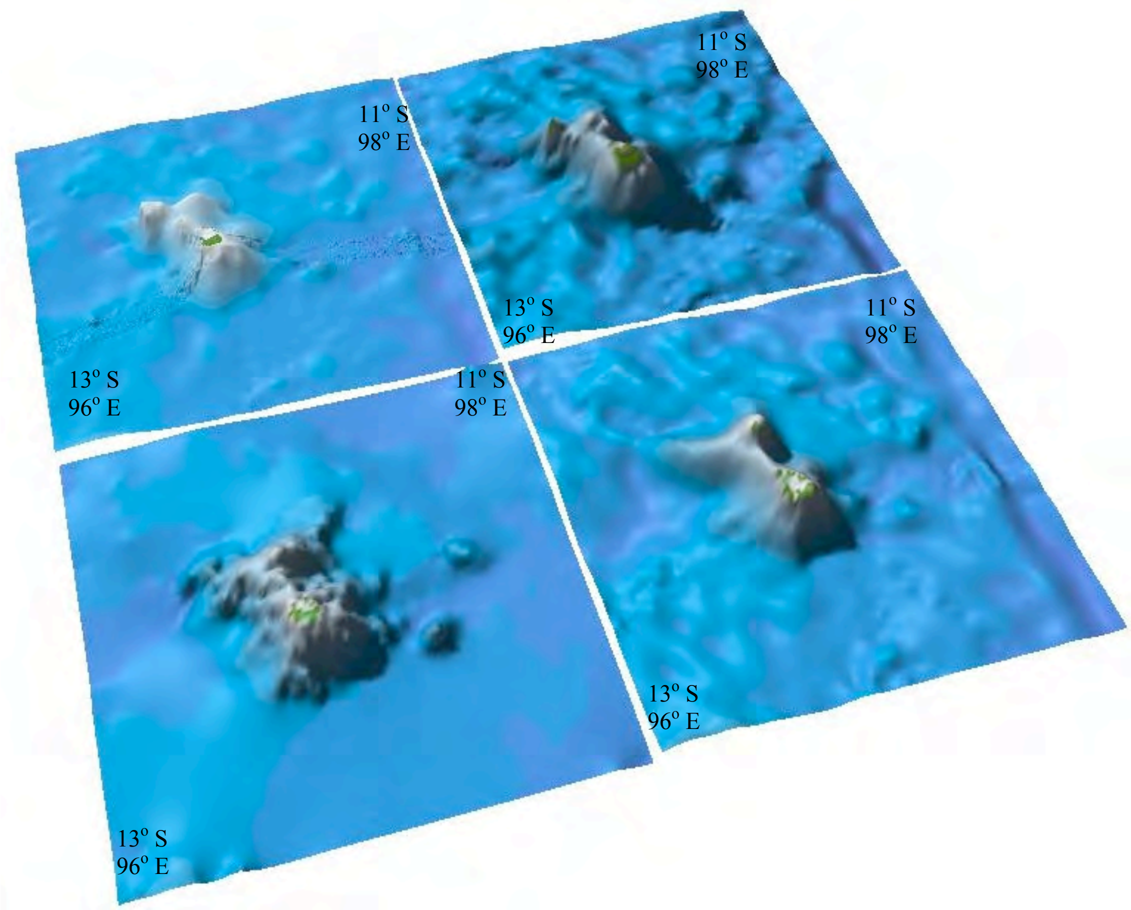


Figure 6: *Comparison of 4 widely used and popular bathymetry grids. Clockwise from the top left: the GA grid, DBDB2, ETOPO1and GEBCO (position markers are approximate only).*

Dataset discussion

Cocos (Keeling) Island is extremely difficult to represent on the scale of 250 metres as many of its islands are no more than 50 metres wide. The ETOPO1 grid seems to be the better of the four grids in respect to the shape of the shelf and land, but appears 150 m too shallow in most areas when compared to survey data for the area. The shape and size of the land in the GA grid is unrealistic, however the raised atoll region is better represented. The purpose of this study is to improve on the Australian bathymetry grid with the inclusion of new bathymetry data as well as topography data and through a thorough assessment of the quality of the data employed.

3. Available Data

BATHYMETRIC DATA

A review of existing bathymetric data holdings at Geoscience Australia and a search for other bathymetric datasets that cover the Cocos (Keeling) Island region was undertaken. Only surveys that fell into the approximate region of 96° to 98° E and 11° to 13° S were considered (Table 1). Basically three data types were found: singlebeam echosounder, multibeam echosounder (swath) and satellite derived bathymetry. The history and characteristics of each dataset are described below.

Table 1: Cocos (Keeling) Island region bathymetry

SURVEY NAME	VESSEL NAME	DATA TYPE	SOURCE INSTITUTION*
"AHS Chart" fairsheet barcodes are as follows: 100014212, 100014213, 100014214, 100014215, 100014216, 100014217, 100014218 and 100014219	HMAS Moresby + others	chart	AHS
Sonne 199	R/V Sonne	multibeam	BGR
FR09/94	R/V Franklin	echosounder	CSIRO
FR07/96	R/V Franklin	echosounder	CSIRO
FR07/99	R/V Franklin	echosounder	CSIRO
FR09/00	R/V Franklin	echosounder	CSIRO
"Outfall survey"	unknown	echosounder	CSIRO
"satellite data"	ALOS satellite	Derived bathy.	GA
Cocos Island bathymetric survey	M/V Sealand	echosounder	DoTaRS
INMD06MV	R/V Melville	echosounder	NGDC
RC0909	M/V Robert D. Conrad	echosounder	NGDC
ODP121JR	M/V Joides Resolution	echosounder	NGDC
V3308	M/V Vema	echosounder	NGDC
V2819	M/V Vema	echosounder	NGDC
VANC10MV	R/V Melville	multibeam	SIO

*AHS=Australian Hydrographic Service, BGR=Bundesanstalt für Geowissenschaften und Rohstoffe, CSIRO=Commonwealth Scientific and Industrial Research Organisation, GA=Geoscience Australia, DoTaRS= Department of Transport and Regional Services, NGDC= National Geophysical Data Center, SIO= Scripps Institution of Oceanography.

Australian Hydrographic Service data

The Australian Hydrographic Service (AHS) acquires and maintains a large collection of bathymetric data for the purposes of hydrographic surveying. Older data that were collected by using a lead line or singlebeam echosounder have generally been collated into a series of bathymetric charts whereas more recent data such as those acquired using multibeam echosounders and airborne lasers are stored in digital data files. The datasets from the AHS are usually supplied in an AHS exchange format (.htf – hydrographic transfer format)

Chart Data

In recent years the AHS has undertaken the major task of digitising its large collection of bathymetric charts. Under a Memorandum of Understanding (MOU) with the AHS, GA now has access to much of these data.

In 2007 GEMD commissioned the digitisation of naval charts for tsunami modelling. The work was carried out by Bebbington Cartographic Pty. Ltd. and covered the charts Aus606, Aus607 and fairsheet survey class SD004. The distribution of the chart data is shown in Figure 7. All data sets have been converted to mean sea level (MSL) and WGS84. The data points can be found on chart AUS606 (http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus606&subchart=0) and on chart (http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus607&subchart=0) AUS607 closer to the island. The dates of data collection are not stated. The positional accuracies are stated as anywhere from 5 m to 500 m. The fairsheet data was collected in 1983 and no positional accuracy is stated.

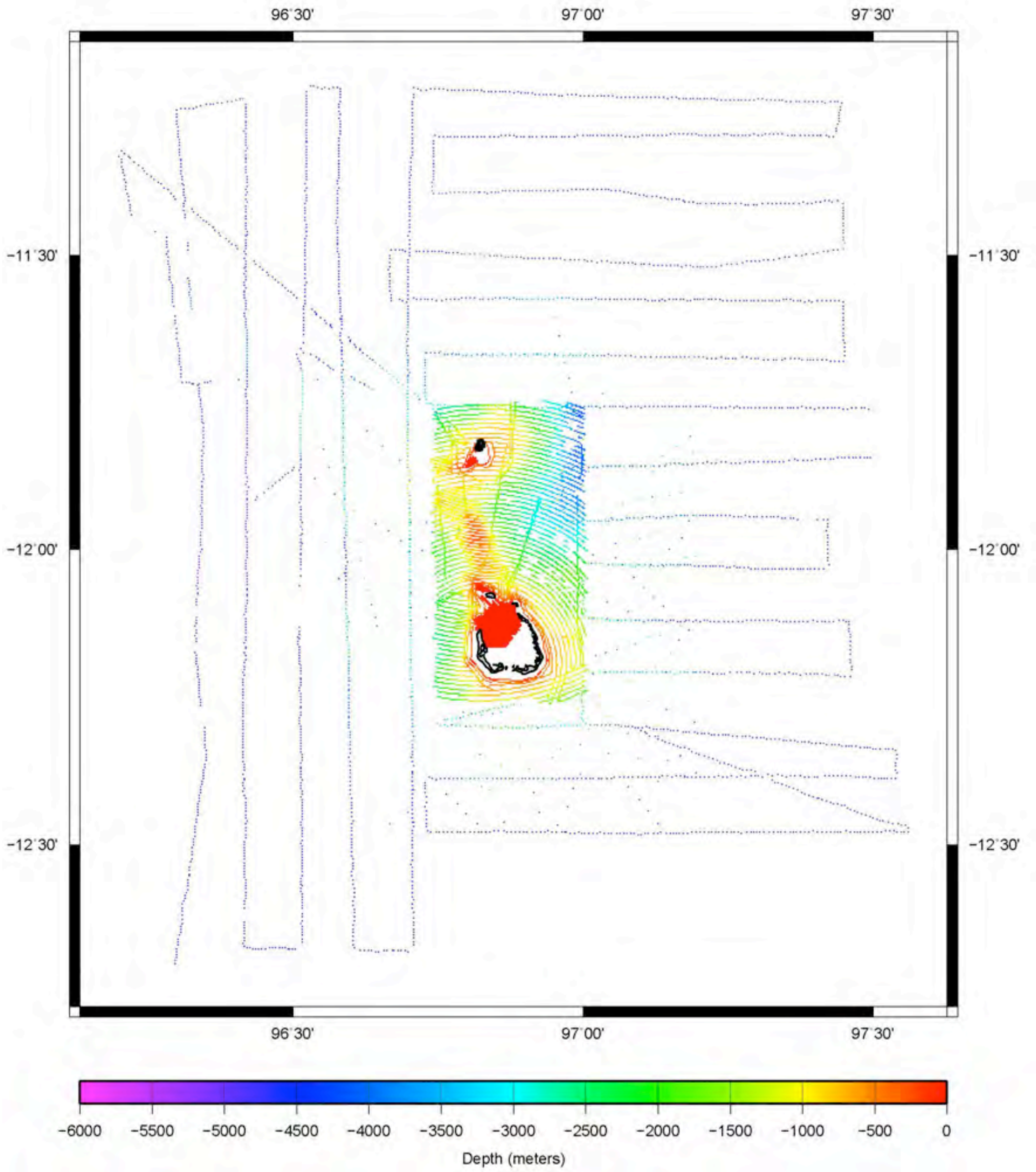


Figure 7: *AHS chart data exhibiting high density near the islands.*

Bundesanstalt für Geowissenschaften und Rohstoffe surveys

Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) is the Federal Institute for Geosciences and Natural Resources in Germany. GA holds the data for one R/V *Sonne* survey undertaken in the Cocos (Keeling) Island region and this is discussed in the next section. More information on BGR can be found from the following website: http://www.bgr.bund.de/cln_101/nn_322882/EN/Home/.

SO-199 (CRISP)

In 2008 the R/V *Sonne* collected swath bathymetry around Cocos (Keeling) Island. As more data was needed for tsunami modelling contact was made with the principal investigator and advice was given as to the best locations to collect new data. Processed swath data was immediately sent to GA at the conclusion of the survey.

The data distribution is shown in Figure 8. The navigation was GPS with a positional accuracy of 2 to 5 m. More information on this survey can be found from Werner et al (2009).

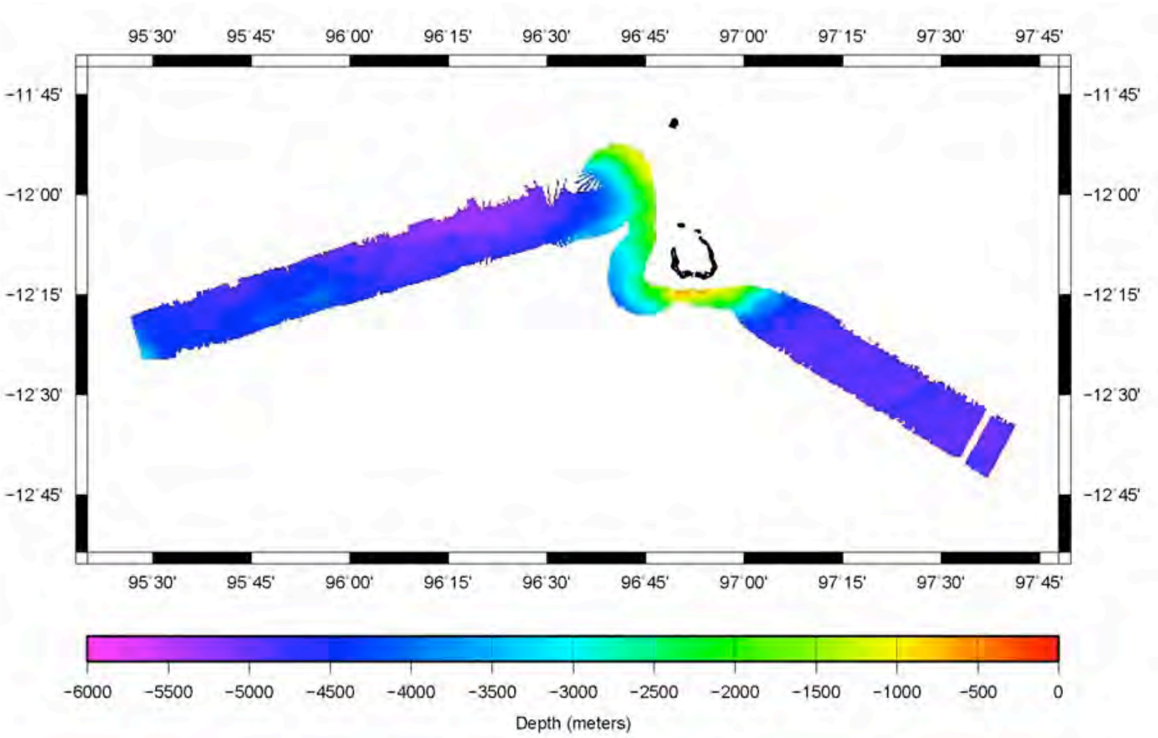


Figure 8: *SO-199 data showing high resolution multibeam very close to the island.*

Marine National Facility surveys

The Marine National Facility is managed by the CSIRO. The CSIRO to date has collected data around Cocos (Keeling) Island on many occasions using the Australian owned vessel the R/V *Franklin*. Under the MOU that GA has with the CSIRO we have data at one minute intervals. For surveys of this vintage GPS would have been used with a horizontal positional accuracy of 100 m. More information on the National Facility can be found from the following website: http://www.marine.csiro.au/nationalfacility/. The data distribution for all the surveys is shown in Figure 9.

FR09/1994

The R/V *Franklin* visited the area in 1994. More details on this survey can be found at the following link: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4797.

FR07/1996

The R/V *Franklin* visited the area again in 1996. More details on this survey can be found at the following link: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4689.

FR07/1999

The R/V *Franklin* visited the area once more in 1999. The data distribution is shown as the high density track in Figure 9. More details on this survey can be found at the following link: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=5360.

FR09/2000

The R/V *Franklin* visited the area for the last time in 2000. More details on this survey can be found at: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=5496.

Outfall survey

This data was obtained from GHD and was used in their storm surge study; (see GHD, 2001).The reference states that the survey was undertaken by the CSIRO. No date, vessel or datum is given and communications with the CSIRO have revealed that they have no record of this survey which indicates that it may not have been done by a CSIRO vessel but perhaps a local one or the CSIRO had no involvement at all. The survey consists of three east-west transects near the sewerage outfall just west of West Island. The data are shown in the inset of Figure 9.

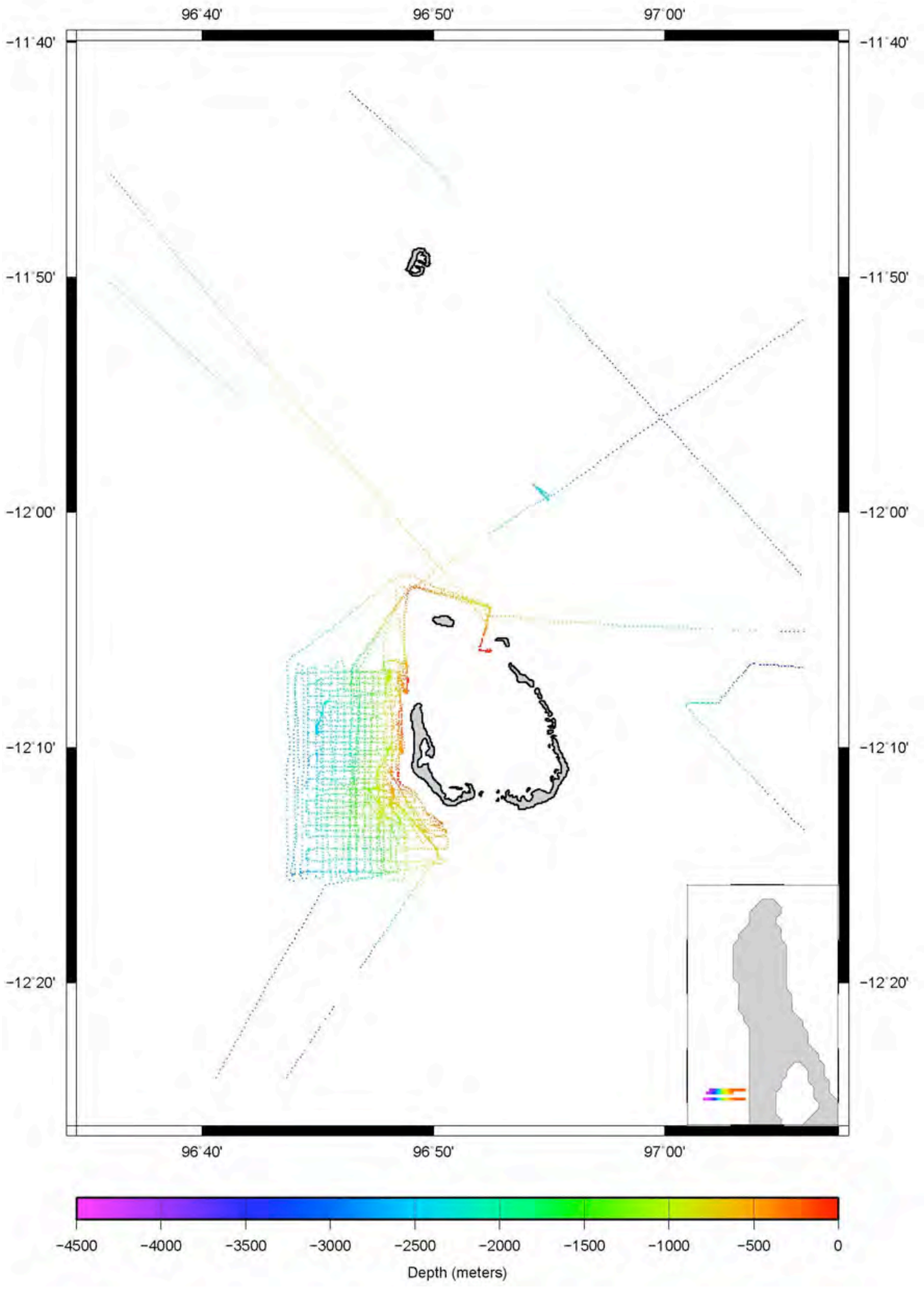


Figure 9: *The CSIRO Franklin data (inset: outfall data just west of West Island with a colour scale -315 to 0 m).*

Department of Transport and Regional Services (DoTaRS) data

In 2002, a company called *Sea and Land Surveying* was commissioned by DoTaRS to survey the shipping channel in the Cocos (Keeling) Island lagoon. The navigation used was GPS with a positional accuracy of 2 to 5 m. The three surveys: Tanker Channel Bathymetric Survey, Blue Hole Anchorage Area Bathymetric Survey and West Island Bathymetric Survey were conducted from August 2002 to March 2003. The data distribution is shown in Figure 10. A survey report has been requested from the surveyor. Contact details are given in the references under Shepherd, but details can also be found in Porritt (2006).

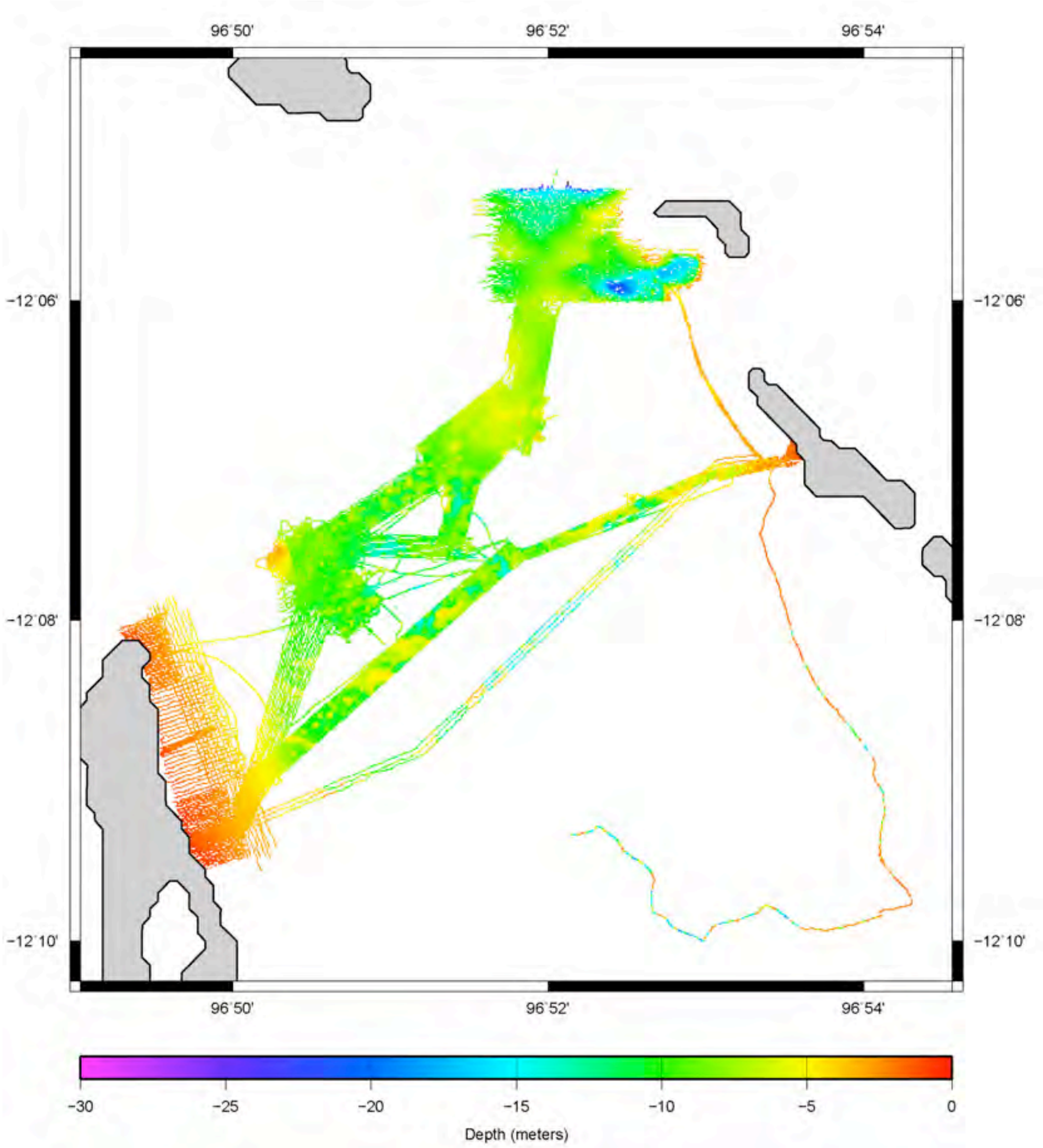


Figure 10: *DoTaRS data showing finer detail in the lagoon.*

Geoscience Australia data

Geoscience Australia has not conducted any marine surveys around Cocos (Keeling) Island. The only dataset originating from GA is multi-spectral satellite data.

Satellite derived bathymetry

In 2007 GEMD processed an ALOS (Advanced Land Observing Satellite) scene which was converted to bathymetry to be used in tsunami modelling. It is a derived data set based on physical equations and is most accurate in shallow water less than twenty metres. The data distribution is shown in Figure 11 and a full explanation of the processing is given in Appendix 1. Only a subset was used for gridding, data was used in the very shallow areas in the south of the lagoon where no echosounder data could be acquired.

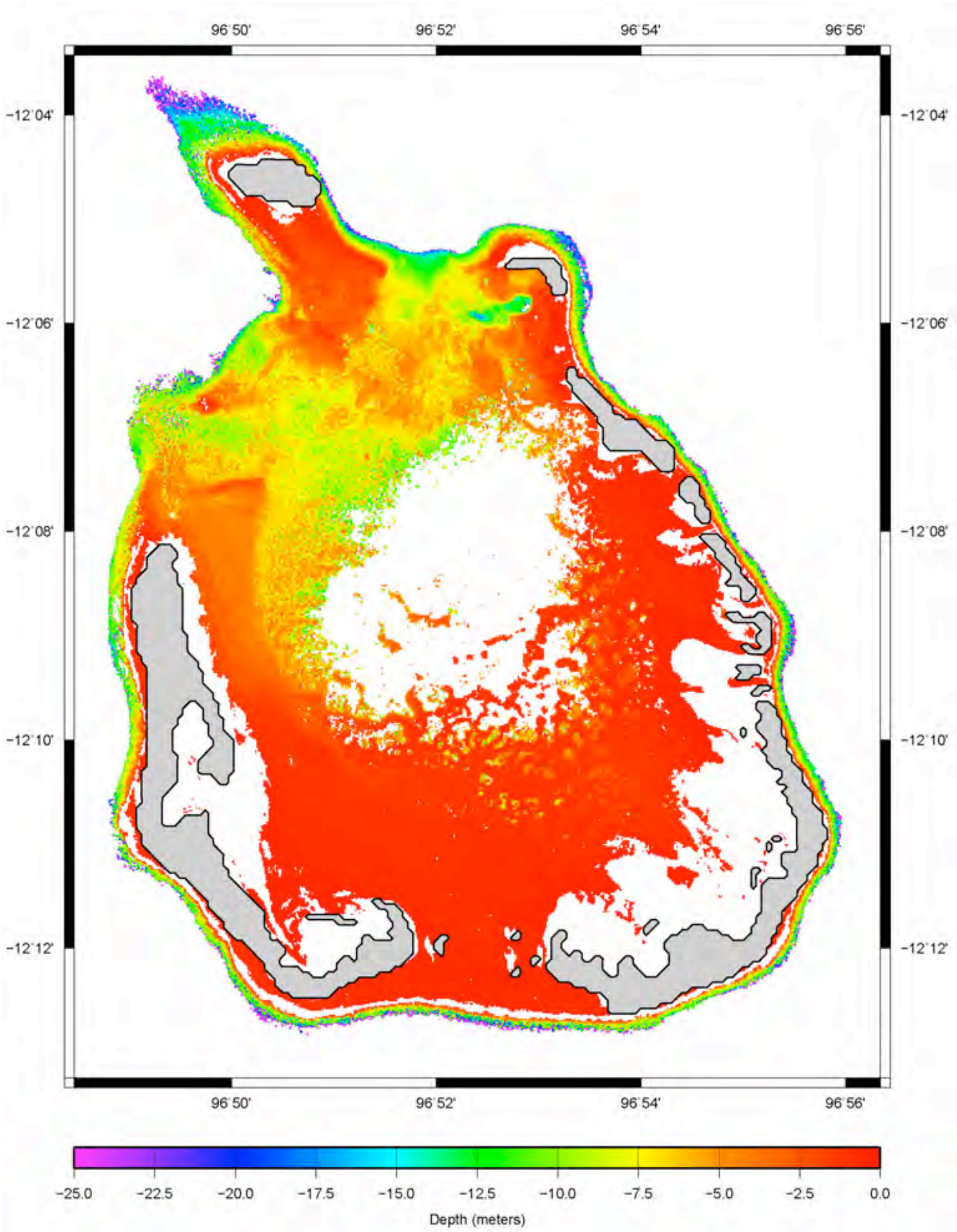


Figure 11: *Satellite Derived Bathymetry showing fine scale detail in the lagoon.*

Scripps Institution of Oceanography data

The Scripps Institution of Oceanography (SIO), University of California, San Diego has a fleet of many vessels and more information can be found from the following website: http://scripps.ucsd.edu/. GA has the data from two R/V *Melville* Cocos Island region surveys, one of them swath. The swath data set was given to GA by SIO. The swath data set is listed below and the other older survey is listed under the NGDC from where it was obtained.

VANC10

In 2003 the R/V *Melville* transited past Cocos (Keeling) Island. The navigation used was GPS with accuracies in the vicinity of 2 to 5 m. The data is shown in Figure 12. Survey details can be found at: http://gdc.ucsd.edu/index.php?page=22&cruiseid=VANC10MV&table=cruise_info.

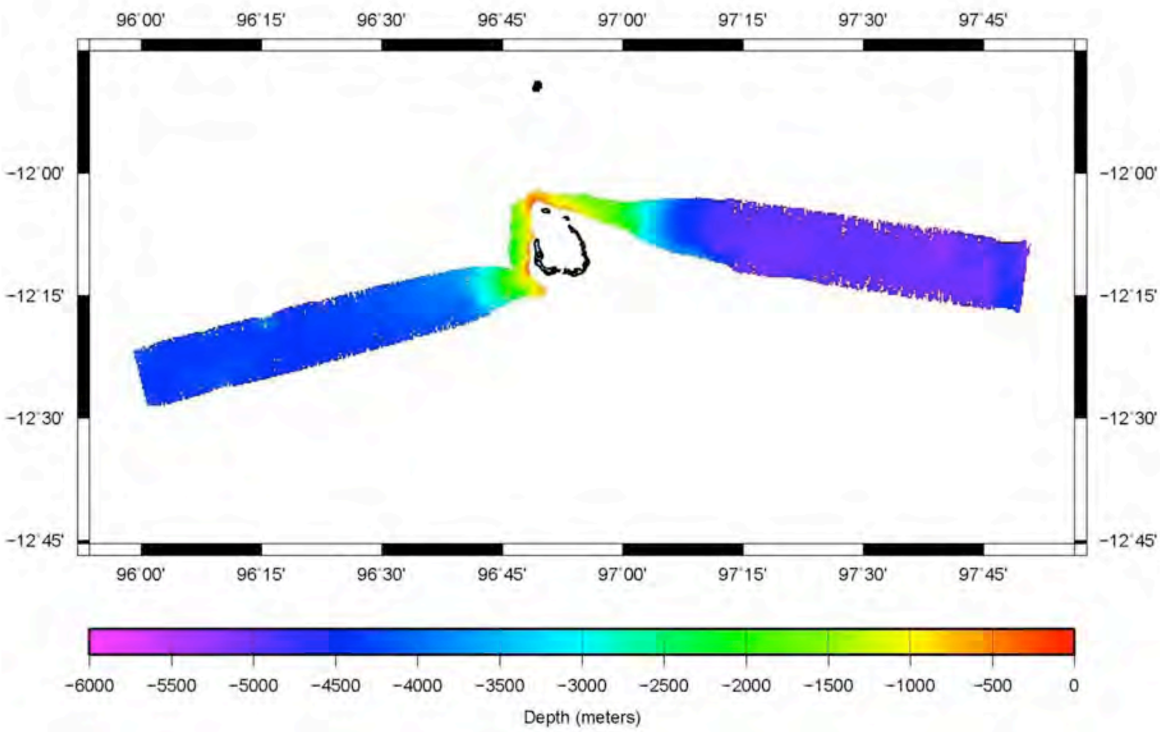


Figure 12: *R/V Melville survey data showing high resolution multibeam close to the island.*

National Geophysical Data Center (NGDC)

The National Geophysical Data Center (http://www.ngdc.noaa.gov) is a part of the US Department of Commerce, National Oceanographic & Atmospheric Administration (NOAA). It is the primary data centre for US derived marine geophysical data, but also houses data from other nations. Suitable data from five surveys were found at this site and their distributions are shown in Figure 13. These surveys are as follows.

INMD06MV

In 1978 the R/V *Melville* was cruising past the coast of Cocos (Keeling) Island with the echosounder turned on. The transit satellite system was used for navigation with horizontal accuracy of 500 to 1500 m. More information on the details of this survey can be found at the following link (http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=INMD06MV&t=102697&s=6&d=7) to the NGDC database.

ODP121JR

In 1988 the R/V *Joides Resolution* was transiting past the coast of Cocos (Keeling) Island. The transit satellite system was used for navigation with horizontal accuracy in the vicinity of 500 to 1500 m. The following link can provide more details on the survey:
http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=ODP121JR&t=102697&s=6&d=7.

RC0909

In 1965 the M/V *Robert D. Conrad* sailed past Cocos (Keeling) Island. No navigation system is stated for this survey, given the vintage it is assumed that a sextant was used with an accuracy of 3,500 to 10,000 m. More details on this survey can be found at the following link:
http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=RC0909&t=102697&s=6&d=7.

V2819

In 1971 the R/V *Vema* was transiting past the coast of Cocos (Keeling) Island. The transit satellite system was used for navigation with horizontal accuracy in the vicinity of 500 to 1500 m together with a sextant with an accuracy of 3,500 to 10,000 m. More details on this survey can be found at: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=V2819&t=102697&s=6&d=7, which is a link to the NGDC.

V3308

In 1976 the R/V *Vema* was transiting past the coast of Cocos (Keeling) Island. The transit satellite system was used for navigation with horizontal accuracy of 500 to 1500 m together with a sextant with an accuracy of 3,500 to 10,000 m. More details on this survey can be found at the following link: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=V3308&t=102697&s=6&d=7, which is a link to the survey details at the NGDC.

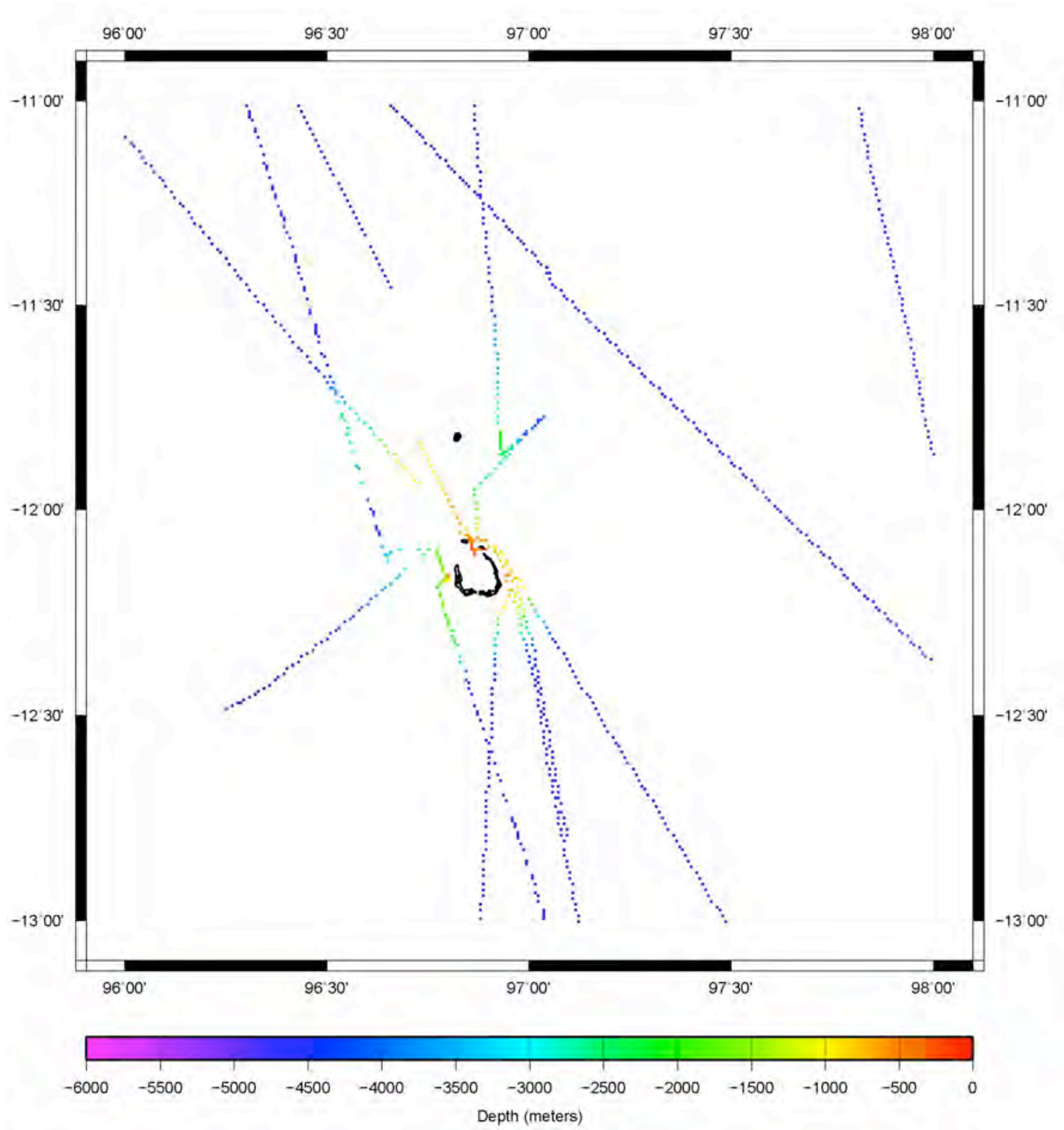


Figure 13: *NGDC data showing surveys of an older vintage.*

TOPOGRAPHIC DATA

The four publicly available bathymetric grids of the Cocos Island area depicted the exposed land surface and coastlines poorly. To rectify this deficiency and to provide some constraints to the bathymetric gridding process, a number of high quality topographic and coastline data sets were evaluated (Table 2). Unfortunately, unlike Christmas, Lord Howe and Norfolk Island very little topographic data exists for Cocos (Keeling) Island and North Keeling Island.

OEMD provided some contours and spot heights taken from their GIS of Cocos (Keeling) Island (see Porritt 2006). Space Shuttle Radar Topography Mission (SRTM) data was available but tree canopies corrupted true topography and were therefore unusable. There is a time line to process SRTM data for Cocos Island to remove the canopy effects, but this has not commenced yet. Also there is a proposed LIDAR survey of the island for the near future. If any of these data sets become available they will be added to the data set of topography.

Table 2: Cocos (Keeling) Island topography.

NAME	RESOLUTION	SOURCE INSTITUTION
contours	0.5 to 100 metres	Geoscience Australia
spot heights	5 to 1000 metres	Geoscience Australia
chart heights	200 to 800 metres	charts
profiles	100 metres	University of Wollongong
SRTM*	90 metres	US Geological Survey

* SRTM=Shuttle Radar Topography Mission.

Onshore Energy and Minerals Division (OEMD) GIS

The GIS of Cocos (Keeling) Island contained contours, spot heights, Department of Lands Administration (DOLA) heights, cadastre heights and ortho control points. All data are in the WGS84 datum. The data are shown in Figure 14.

Chart Heights

Some other spot heights were digitised from the Natmap Topographic Map 1:25000 Cocos (Keeling) Islands Edition 1. The data was assumed to be in WGS84. The data are shown in Figure 14.

Satellite Derived Coastline

A ten metre resolution coastline was obtained from an ALOS satellite scene. The data are in WGS84. A full explanation is given in Appendix 1 and the data are shown in figure 14.

Profiles

Height profiles across the island were conducted by a team led by Colin Woodroffe (Woodroffe and Mclean, 1994) from the University of Wollongong and are shown in Figure 15. Profiles D and E were not used as Home Island has adequate contours and spot heights. Profiles (not shown) on West Island were not used as adequate contours and spot heights also exist. The profiles A, B, C, F, G, H, I, J, R and Q were used to supplement the sparse topography on those islands. The profiles were digitised from the original diagrams shown in Figure 15. The start and end positions were geo-located in ArcMap with the aid of the satellite image shown in Figure 16. The geo-located profiles were then exported as interpolated 10 metre points. The positions were assumed to be in WGS84.

DoTaRS Heights

Some of the surveys conducted by *Sea and Land Surveying* also included a small amount of on-shore height data on Home and West Island. The data was assumed to be in WGS84.

Space Shuttle Radar Topography Mission (SRTM) data

Topographic data were obtained from the USGS web site. The dataset has a resolution of 90 metres with values rounded to the nearest integer. The positional accuracies are stated as 20 metres in both horizontal and vertical directions. More information on the SRTM data set can be found from the following link: http://srtm.usgs.gov/. SRTM data was only used for North Keeling Island. The data mainly contained elevation at tree canopy height so it was adjusted using the nearest spot height and profiles (y and z) from the University of Wollongong. The data distribution is shown in Figure 18.

Estimated Heights

With the exception of Home and West Island some locations on other Islands had to have their heights estimated. As shown in figure 15, the islands are not flat, however, interpolation over sparse topography data would not reproduce this feature, and the end result may be that the islands appear mostly flat. Therefore data points were interpolated based on the profiles from figure 15. This was done in ArcMap by digitising points close to existing known heights such as those listed in Table 2. These points were given values close to the known ones and then exported to an ASCII file. This assisted the gridding process especially on the 10 metre scale. An example data distribution is shown in Figure 18 for North Keeling Island.

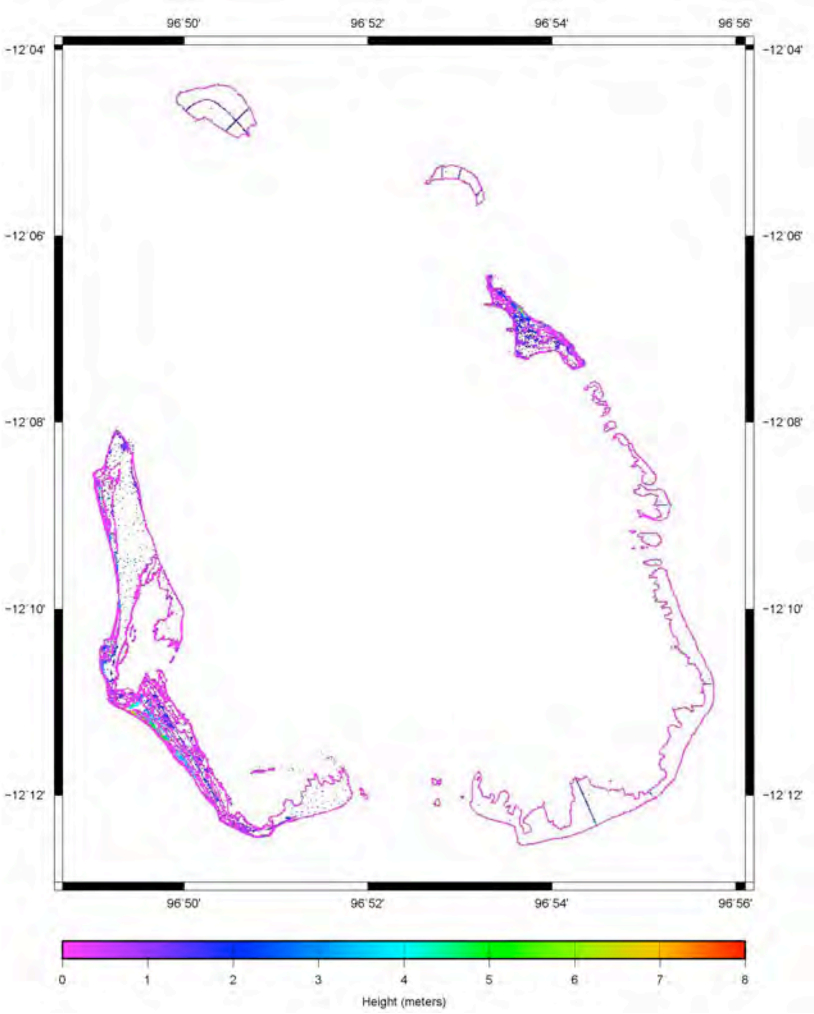


Figure 14: *Cocos (Keeling) Island showing all available topography.*

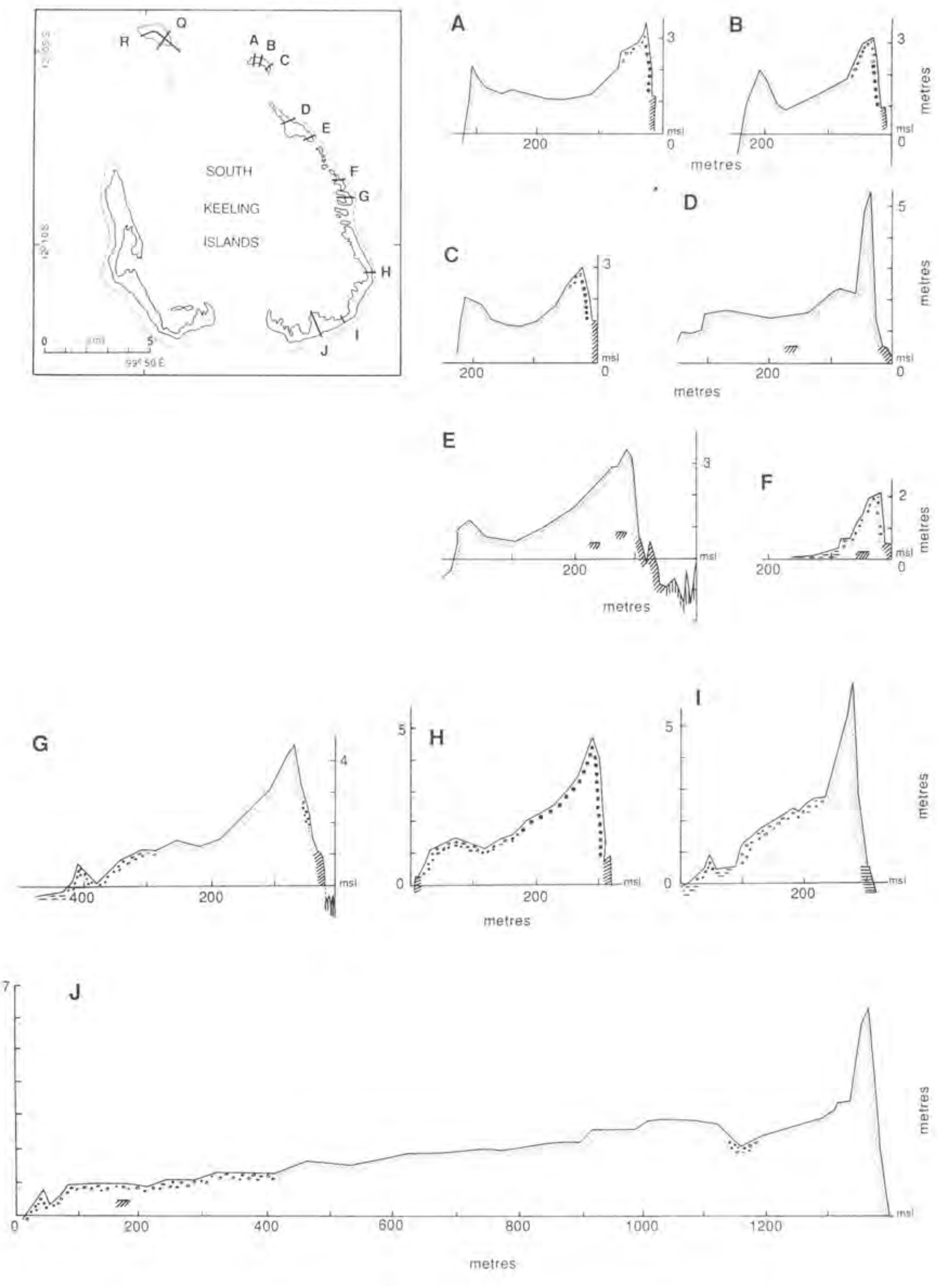


Figure 15: *Profiles across Cocos Island (figure used with permission, Woodroffe 1994).*

OTHER DATA

Charts and Images

Though naval charts, satellite images and aerial photography are not part of the data set to be gridded they serve as a valuable tool for assessing the data. The position of coastlines, islands and general depths and heights can be cross-checked against these images in visualisation software mentioned in the following chapters. In this work chart number AUS607 obtained from the AHS (under the MOU: http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus607&subchart=0), was used and is shown in Figure 17. Satellite imagery which were obtained from the Cocos Island GIS, had superior geo-referencing than the chart was also used, and an example is shown in Figure 16.

Figure 16: The Cocos (Keeling) Islands Main Atoll True Colour ALOS AVNIR2 image (land shown as green polygons).

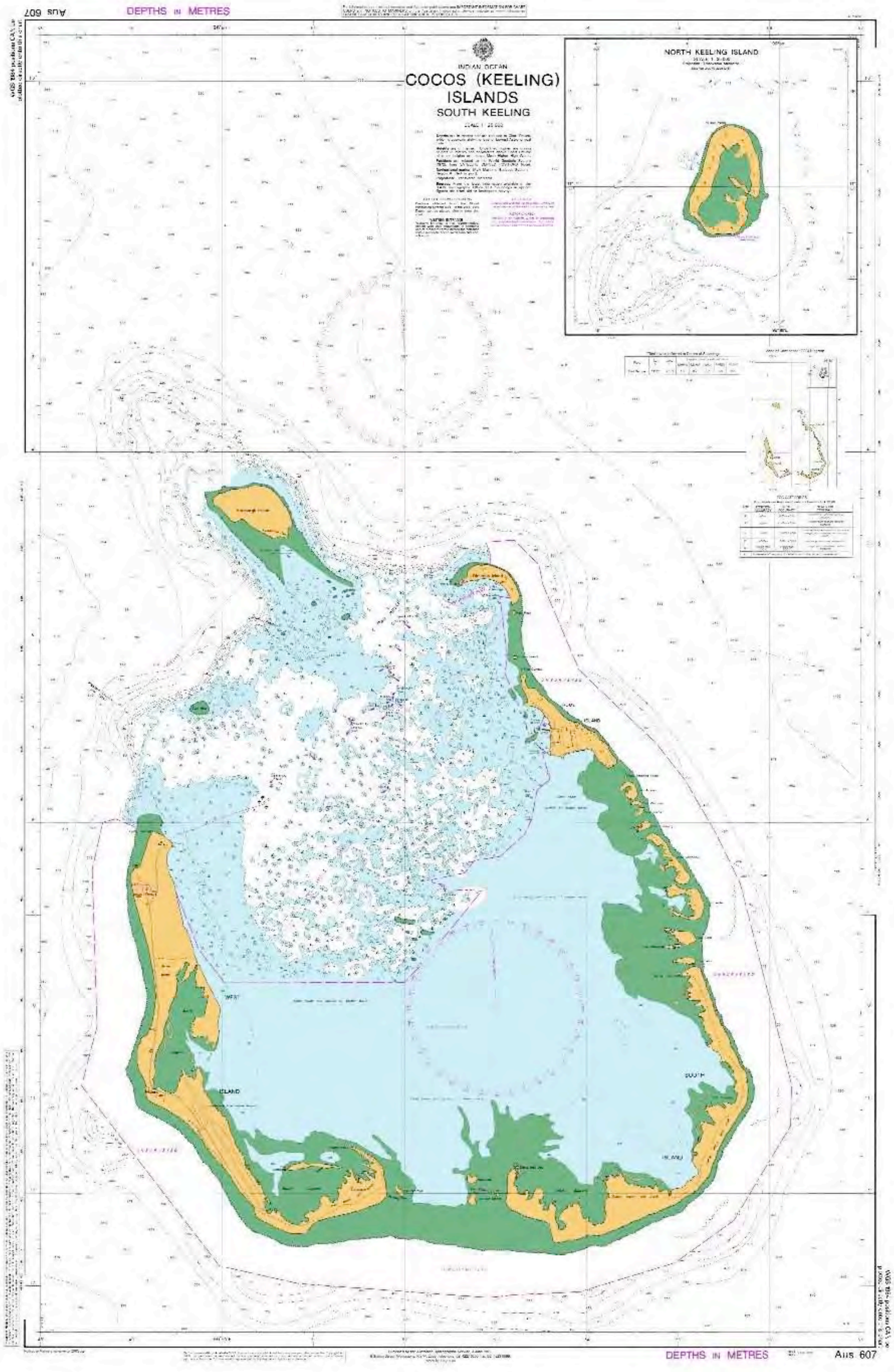


Figure 17: Chart AUS607 (used under licence AHS, not to be used for navigation).

4. Data Processing

The various datasets had all undergone some level of data processing prior to their importation into the gridding algorithm. Whilst much of this work was conducted outside of this project, the data processing is a key component in the process of making a valid gridded surface. As a first step, all data sets were converted to the WGS84 datum and if possible the depths were referenced to mean sea level. The following gives a brief description of the processing steps employed.

SWATH PROCESSING

Multibeam data are usually partially processed at sea during data acquisition. This phase of processing usually concentrates on the removal of erroneous beams. At GA, all of the available multibeam data have been imported into the CARIS processing application (http://www.caris.com/) and undergone further cleaning of bad beams as well as detailed corrections for tides and speed of sound variations. As the number of beams in the multibeam datasets was so large, the data were internally gridded within CARIS and exported as a 100 metre ASCII xyz grid. These xyz data formed the basis of further work using the multibeam data.

SINGLEBEAM ECHOSOUNDER PROCESSING

All echosounder data had already been processed to some degree by the source institutions. These data have also been examined a number of times within GA by other projects and any serious problems had been removed. Invariably the bathymetric soundings are referenced to the sea surface at the time of observation and not mean sea level. This was not an issue as most of the singlebeam soundings were in deep water.

CHART DATA

These data were entirely processed by the AHS. No further processing was undertaken at GA. The vertical datum was the Lowest Astronomical Tide (LAT) and a small (0.7 m) correction was applied to correct them to mean sea level.

SATELLITE DATA PROCESSING

The shallow water satellite-derived bathymetry was obtained by processing multi-spectral data from the ALOS satellite. Briefly the processing steps involved the masking of land and inter-tidal areas, a deglinting and an atmospheric correction procedure followed by the extraction of a bathymetry value utilising the SAMBUCA algorithm (Wettle & Brando, 2006), and validated against existing bathymetry in the area. The final depths were then tide and datum adjusted. For further details on the data processing and methodology refer to Appendix 1.

5. Analysis and QC of the Bathymetric Data

The fully processed data sets were checked against each other for consistency as an additional check of data quality. Two tools were used extensively in an iterative fashion to achieve this: Fledermaus and ArcMap.

FLEDERMAUS

Fledermaus is a bathymetry display and processing tool which allows data points to be viewed in 3D (http://www.ivs3d.com/). In this work it was used to compare data sets from different surveys and assess their reliability. Included in the Fledermaus set of tools is a program called DMAGIC. It was used to create shaded 3D terrain models which where then inspected for data and gridding problems.

ARCMAP

ArcMap (http://www.esri.com) was used to visualise the spatial distribution of the survey data, look at different surveys in relation to each other, delete suspect or incorrect data points and delete inferior surveys in the regions where they overlapped with more reliable swath surveys. This was done in conjunction with Fledermaus. The final data points were then exported in ASCII xyz format ready to be gridded.

PROCEDURE

All final processed data sets were loaded into ArcMap, except for the swath data where only a geotif was loaded to show the spatial extent of the multibeam coverage (the actual multibeam dataset was too large for ArcMap). In deciding which data points to keep for the gridding process, the following decisions were made:

- All data points that fell on areas covered by swath datasets were immediately discarded.
- Data points adjacent to swath data were checked to see if they were consistent with the multibeam data.
- All surveys that intersected with each other were checked for cross-over errors. Interestingly, very few soundings from the singlebeam echosounder surveys needed to be deleted.

The data were then checked with Fledermaus in 3D for similar inconsistencies. Here it was found that many of the digitised chart soundings were not consistent with surrounding echosounder data. Much of this inconsistency could be attributed to inferior navigation in the older chart data, but the inconsistency possibly stems from the physics of the original echosounders employed. These echosounders probably had a significant beamwidth (> 30°) which would lead to shallower upslope depths being detected in areas of steep bottom slope. Such a situation is observed in the digitised chart data immediately south of Cocos Island (Figure 7). The east-west transects are in an area of steep slope and wherever they overlap multibeam data (which have a very small beamwidth of less than 2°) they are consistently shallower. On the other hand, the north-south transects in the digitised chart data are in deeper water with a much smaller slope and are in agreement with multibeam data where the two datasets overlap.

Clearly the physics of the acquisition must be well understood and accounted for when making a bathymetric grid. Furthermore hydrographic charts are principally for safety of navigation, reporting shallower than actual water depths is not a problem in such work and correcting for diffraction effects from pronounced submarine topographic features is not routinely undertaken. For bathymetric mapping however, all echosounder observations should be corrected for these diffraction effects if the beamwidth of the instrumentation and the slope are significant.

As mentioned earlier ETOPO1 data were about 150 m too shallow when compared with survey data. It was decided not to use any ETOPO data to fill in areas of low data density and that unsupported features in the data could be due to processing artefacts rather than real bathymetry. For more information regarding issues with the ETOPO data set consult Marks and Smith (2005).

The topography datasets were also checked against georeferenced TIFF images of the island. Contour data from the OEMD GIS were used, as well as spot heights and the profile data, also a small portion of SRTM data were used for North Keeling Island. The final available data for North Keeling Island are shown in Figure 18.

Multi-spectral satellite derived bathymetry can have a high spatial resolution; however it is only an estimate and therefore inferior to good echosounder bathymetry. In this work it was used in areas where no bathymetric data was present; therefore only in very shallow regions in the south of the lagoon. The white areas of the lagoon in Figure 7 are an indication of where it was utilised.

The process was very iterative in nature with both ArcMap and Fledermaus being used to make decisions. When finished, the final quality controlled data points showed good general agreement with each other and were considered suitable to be gridded (Figure 19).

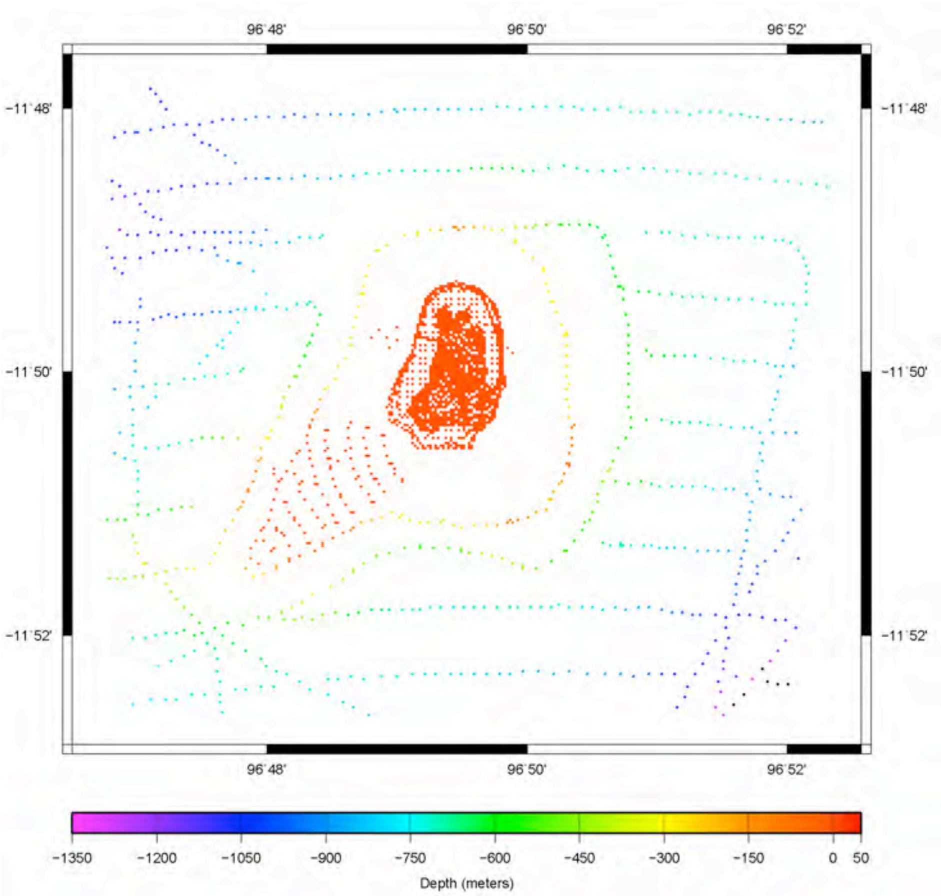


Figure 18: *North Keeling Island data density.*

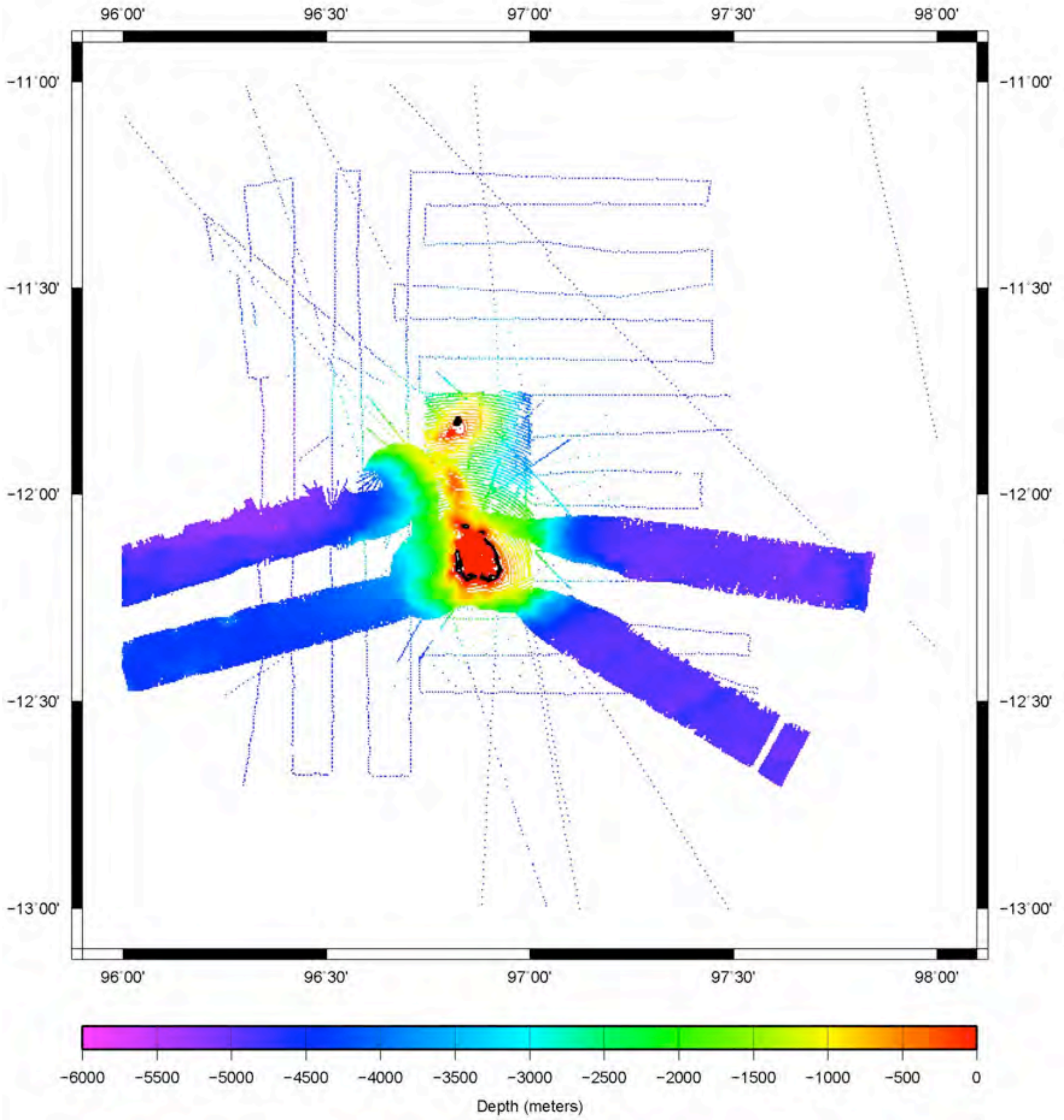


Figure 19: *The final dataset showing all data used to create the final grid including: satellite, multibeam, chart and singlebeam echosounder.*

6. Gridding

PRELIMINARY CONSIDERATIONS

It is possible to produce a gridded surface with any cell size subject to the limitations of the software available and the computer used. The data however can only support a cell size that fits the sampling interval contained in the data set. In an area such as the Cocos (Keeling) Island the data sources and their sampling densities vary widely (Table 3). As a result some areas will be able to be gridded with a fairly small cell size, whilst other areas can only justify a much coarser cell size. Even in the areas where very coarse cell sizes are warranted, it is often necessary to produce a grid at a finer cell size to make the resultant grid visually appealing, even though the data cannot support it.

Table 3: Data density

SURVEY NAME	DATA TYPE	DURING ACQUISITION	AS USED IN THIS WORK
Shallow Lagoon Region			
Cocos Is. Bathy Survey	echosounder	2 - 20 m	2 - 20 m
"Satellite data"	derived bathy.	10 m	10 m
"AHS Chart inner"	chart	unknown	25 m
Raised Atoll Region			
"Outfall survey"	echosounder	unknown	10 m
"AHS Chart inner"	chart	unknown	25 m
FR07/99	echosounder	unknown	50 - 200 m
Sonne 199	multibeam	28 -130 m	100 m
VANC10MV	multibeam	17 – 77 m	100 m
FR09/94	echosounder	unknown	300 m
FR07/96	echosounder	unknown	300 m
FR09/00	echosounder	unknown	300 m
Deep Water Region			
Sonne 199	multibeam	28 -130 m	100 m
VANC10MV	multibeam	17 – 77 m	100 m
RC0909	echosounder	unknown	800 m
V3308	echosounder	unknown	1400 m
INMD06MV	echosounder	unknown	1700 m
V2819	echosounder	unknown	1700 m
ODP121JR	echosounder	unknown	1800 m
"AHS Chart outer"	chart	unknown	3000 m

For the singlebeam data sets the table shows along track data density as the distance between points. As the lines of the ship's tracks are often kilometres apart, this measure of data density is not all that meaningful but it is all that is available. Multibeam data density contains an along-line and cross-line component and varies with water depth. Sometimes these two measures can be quite different. Once again, the values are more qualitative than quantitative. It was found necessary to split the chart data into "inner" and "outer" sets as there was a considerably higher data density in the areas closer to the islands.

A decision was made to produce four grids. A fine scaled grid with a 10 m cell size was seen as possible in the lagoon of the island. A 50 m cell size grid would be suitable over the raised area surrounding Cocos Island, whilst a 100 m cell size grid would be appropriate for the immediate area around Cocos and North Keeling Islands. A 250 m cell size grid was made of the entire region to compare with previous grids.

GRIDDING PROCESS

Various gridding packages were available to this study but it was decided to use the Intrepid (Des Fitzgerald and Associates: http://www.intrepid-geophysics.com/ig/index.php) application as it is widely used at GA and can handle large separate datasets. The gridding method employed was nearest neighbour with minimum curvature smoothing (Billings and Fitzgerald 1998, Briggs 1974).

As mentioned earlier, CARIS had been used to grid the multibeam data prior to making an export. This gridding operation is viewed as a “data thinning” exercise rather than being part of the gridding process, exporting the multibeam data to a more useable data volume. Data were exported at one resolution (100 m cell size) from CARIS.

All of the data are imported into Intrepid Point Databases, a gridding job is set up with the required parameters and a batch job executed. The final product is an ERMapper compatible grid file that can be displayed using ERMapper or converted into any other grid format. A cosmetic clip was applied to the edges of the grids to remove possible edge effects.

On the examination of the resultant grids it was found that there were some minor holes or rises that were not supported by the data in the final data set. Regions most affected were very close to land where the lack of bathymetric data and the gradients from sea to land produced gridding artefacts. The problem was reduced by introducing “control points”. These points were inserted into areas where the interpolation had created unrealistic values. The data points were interpolated by using an average of neighbouring points. The data were then re-gridded and the artefacts disappeared.

All final grids were validated against the original data points. This was done by importing the final grids into DMAGIC and creating 3D DEM surfaces. These were viewed in Fledermaus with the original data points overlaid. All data points fell on this surface, which was to be expected as an option in Intrepid was chosen to honour the original data points. This final check was also necessary to confirm that the interpolation had worked.

Tables 4 to 7 and their accompanying discussion detail the parameters used in the production of the various grids. The large values used for the maximum iterations and extrapolation limit were chosen to ensure that the maximum residual was met and that large gaps in the data were completely interpolated over leaving no null values. These gridding parameters had no significant increase in computation time.

Cocos (Keeling) Island Regional 250 metre grid

The Cocos (Keeling) Island regional 250 metre (or 9 second of arc) grid is shown in Figure 20. It uses all the data that is shown in Figure 19. The computational parameters used in Intrepid are shown in Table 4. The grid on this scale is a good representation of the regional bathymetry. All the original data were honoured and only one gridding artefact was detected. This is in the north-west of the grid where some small oscillations have been produced due to interpolation of sparse data. However, it is still a significant improvement of any grid so far at this resolution.

Table 4: Intrepid gridding parameters for the ~250 m grid.

PARAMETER	VALUE
Latitude range	-13^0 to -11^0
Longitude range	95.5^0 to 98^0
Cell size	0.00225 degrees (~9 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2000
Maximum residual	0.01 m
Extrapolation limit	2,000 cells

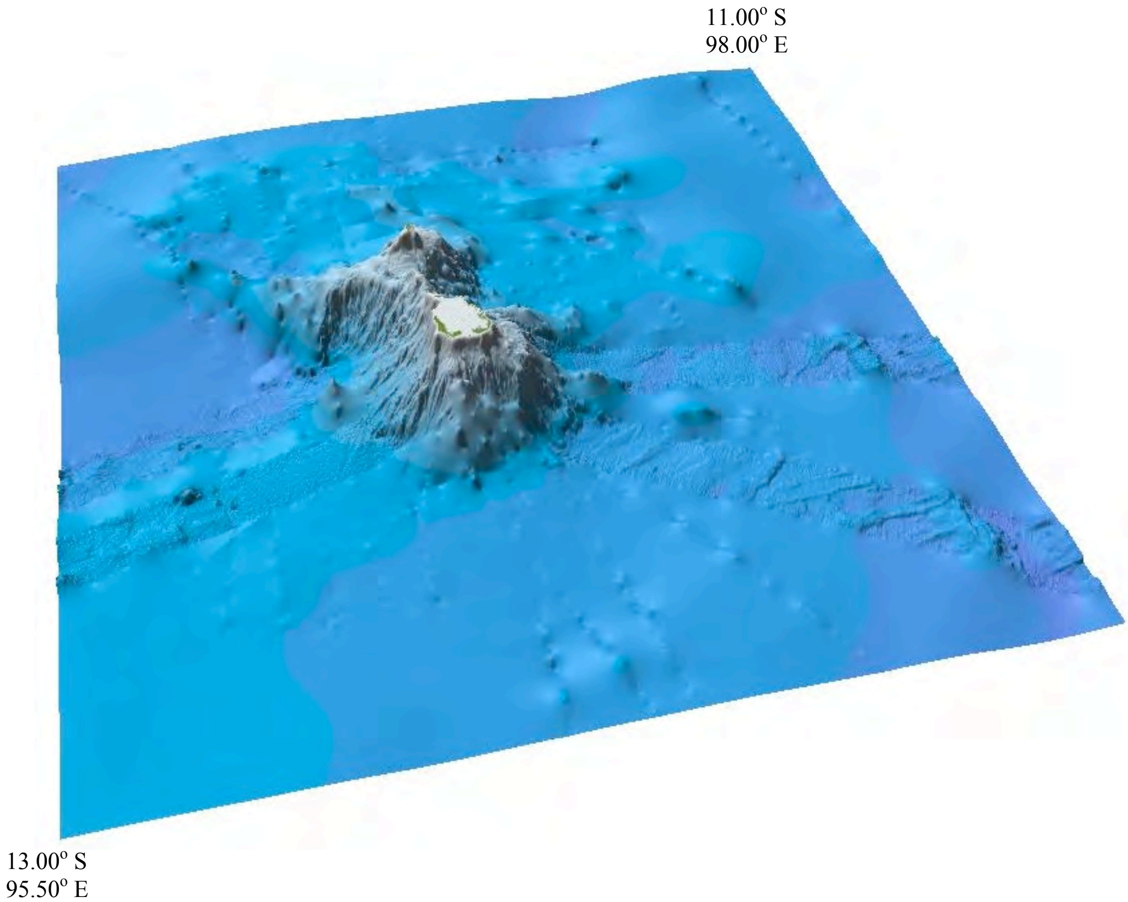


Figure 20: *The Cocos (Keeling) Island 250 m grid (vertical exaggeration 4x, position markers are approximate only).*

Cocos (Keeling) Island 100 metre grid

The higher resolution grid is shown in Figure 21. It uses a subset of the data shown in Figure 19. The computational parameters used in Intrepid are shown in Table 5. The grid on this scale is a very good representation of the regional bathymetry and the interpolations have seemed to have worked well except for the region as mentioned in the previous section. All the original data were honoured and no other gridding artefacts were detected.

Table 5: Intrepid gridding parameters for the ~100 m grid.

PARAMETER	VALUE
Latitude range	-12.7205^0 to -11.15^0
Longitude range	96.16^0 to 97.6036^0
Cell size	0.0009 degrees (~3 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2,000
Maximum residual	0.01 m
Extrapolation limit	1,000 cells

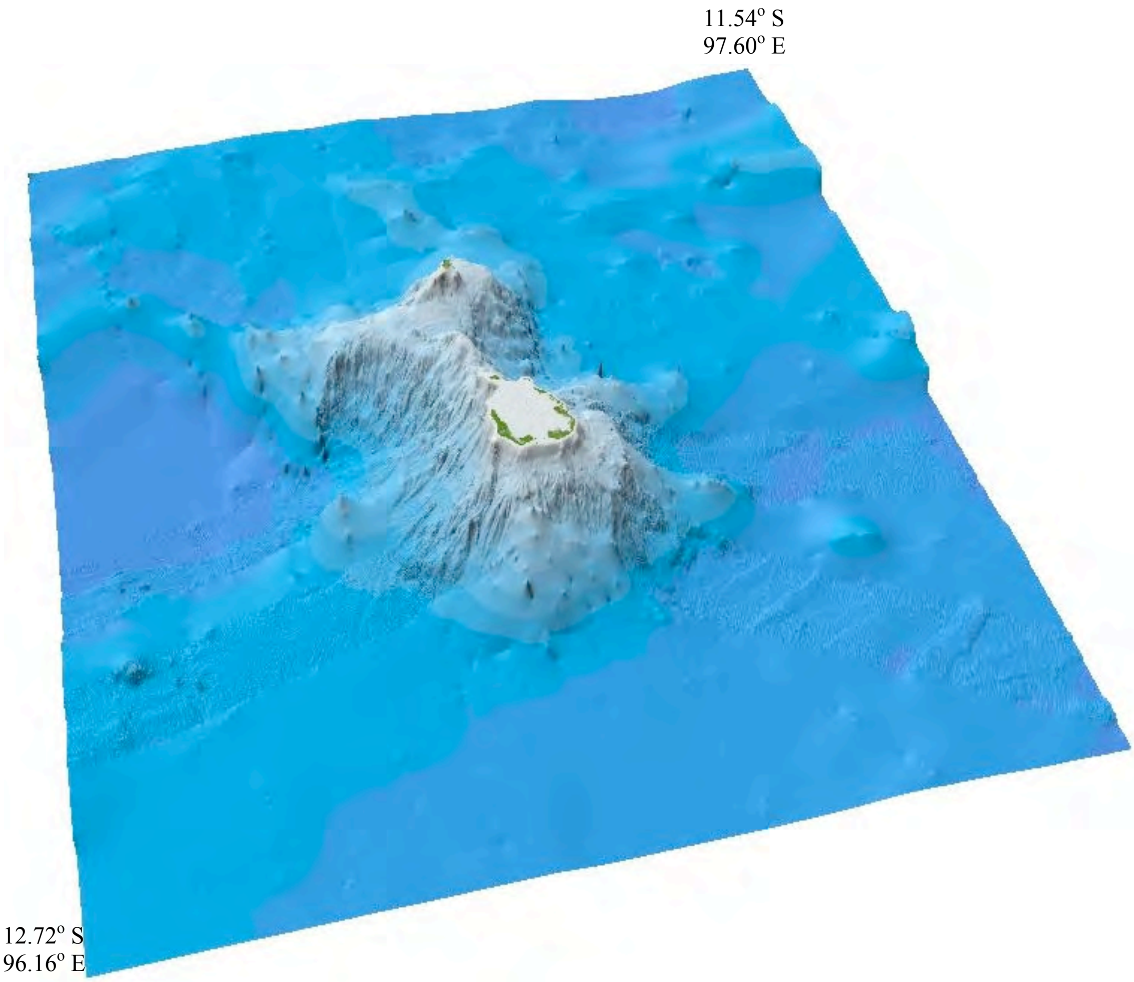


Figure 21: *The Cocos (Keeling) Island 100 m grid (vertical exaggeration 4x, position markers are approximate only).*

Cocos (Keeling) Island 50 metre grid

The even higher resolution grid is shown in Figure 22. It uses a subset of the data shown in Figure 19 as described for the 100 m grid. The computational parameters used in Intrepid are shown in Table 6. The grid on this scale is a good representation of the regional bathymetry and it is probably the first time the area has been gridded at this resolution. All the original data were honoured and no gridding artefacts were detected.

Table 6: Intrepid gridding parameters for the ~50 m grid.

PARAMETER	VALUE
Latitude range	-12.3015^0 to -11.73^0
Longitude range	96.55^0 to 97.2011^0
Cell size	0.00045 degrees (~1.5 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2,000
Maximum residual	0.01 m
Extrapolation limit	1,500 cells

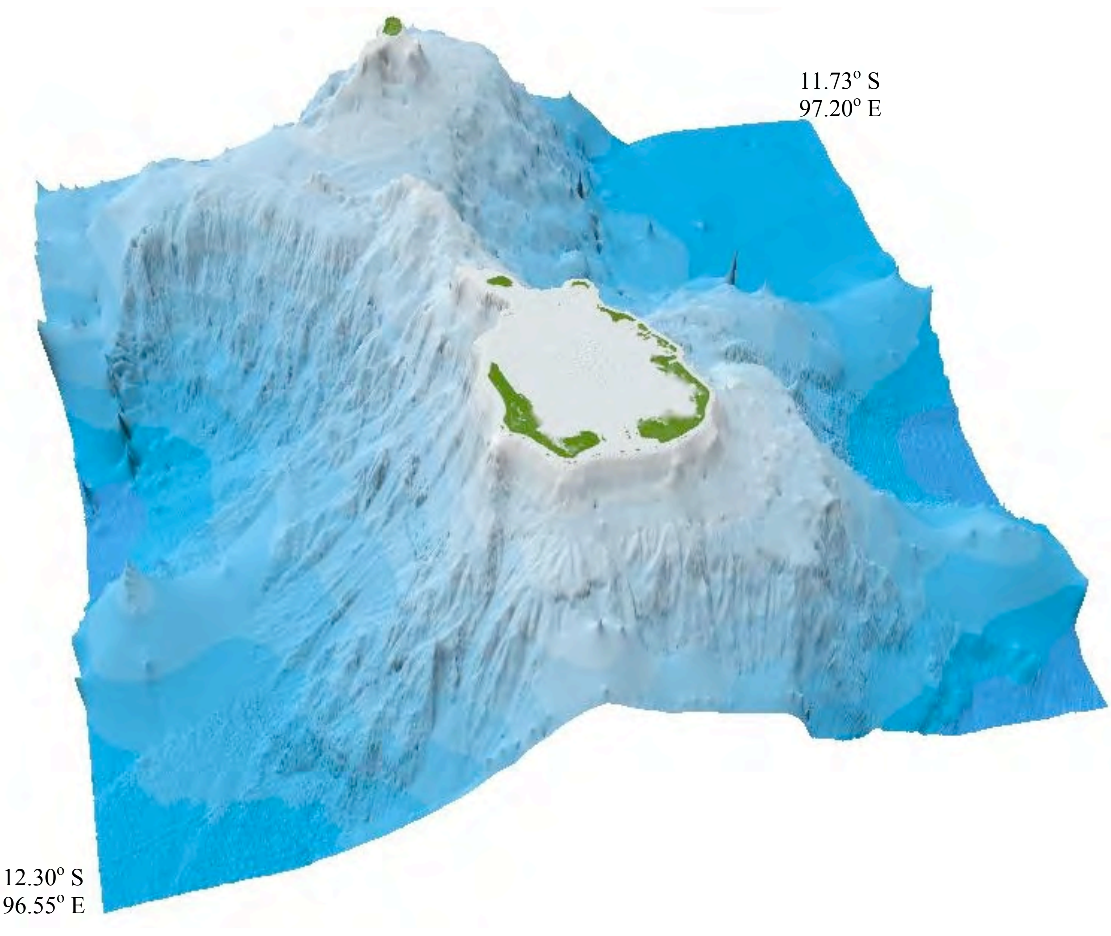


Figure 22: *The Cocos (Keeling) Island 50 m grid (vertical exaggeration 4x, position markers are approximate only).*

Cocos (Keeling) Island 10 metre grid

An extremely high resolution grid focusing on the land and the lagoon of Cocos (Keeling) Island is shown in Figures 23 and 24. The computational parameters used in Intrepid are shown in Table 7. The grid on this scale is a good representation of the lagoon and it is probably the first time the area has been gridded at this resolution. All the original data were honoured and only minor gridding artefacts such as visible ship's tracks were detected. The use of satellite bathymetry at 10 m resolution has made this grid possible as data was lacking in the very shallow areas. This grid has been compared with satellite data and many fine scale features have been reproduced. When compared to the GHD grid, the grid here has more detail in the land and shallow water areas. The use of satellite derived bathymetry make this grid superior as estimation based on imagery and reef profiles was heavily used in the GHD grid. Figure 25 shows a profile across the region; the raised atoll can clearly be seen.

Table 7: Intrepid gridding parameters for the ~10 m grid.

PARAMETER	VALUE
Latitude range	-12.24^0 to -12.045^0
Longitude range	96.8^0 to 96.95^0
Cell size	0.00009 degrees (~0.3 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2000
Maximum residual	0.01 m
Extrapolation limit	1000 cells

***Figure 23:** The Cocos (Keeling) Island 10 m grid (vertical exaggeration 4x, position markers are approximate only).*

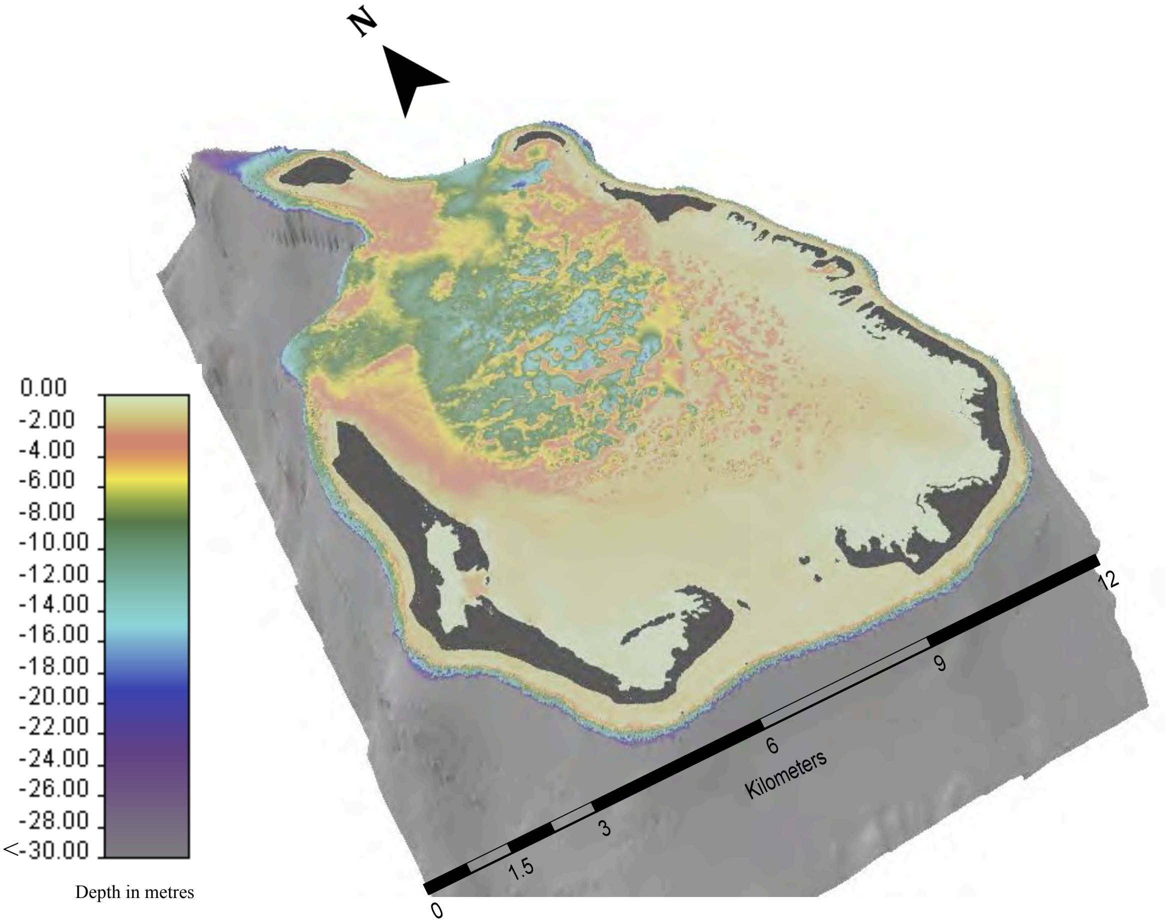


Figure 24: *The Cocos (Keeling) Island 10 m grid with a reef palette (vertical exaggeration 4x).*

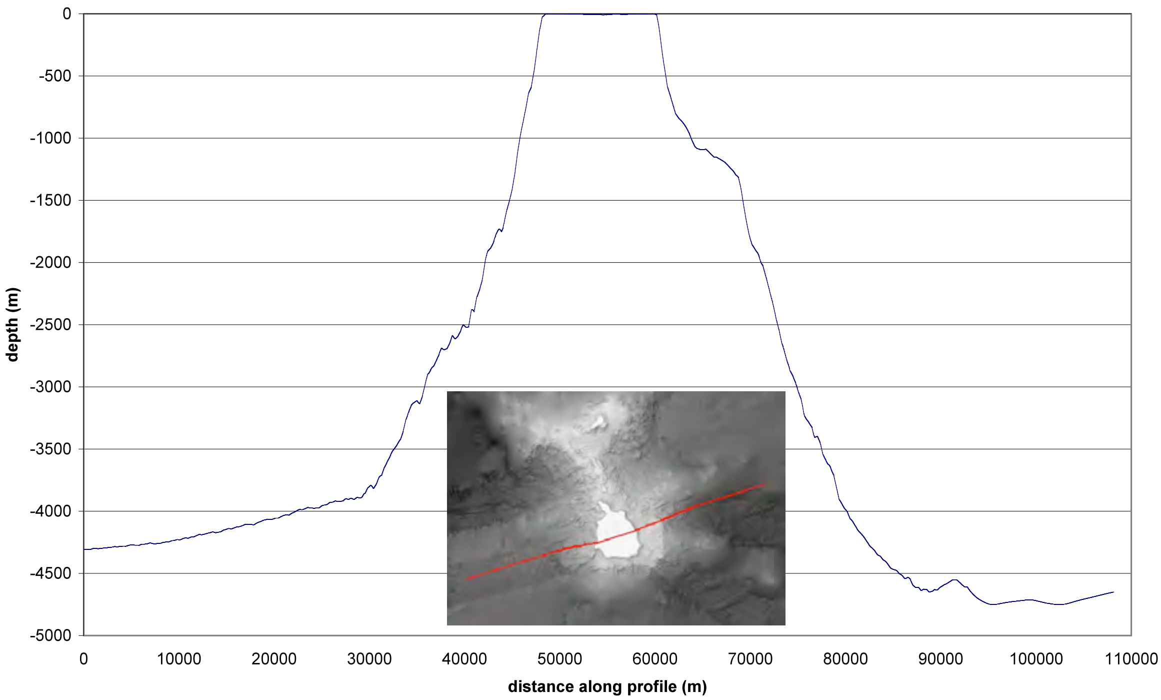


Figure 25: *Cocos (Keeling) Island west-east profile (inset: profile path in red).*

7. Final Grids

The Final Grids are known as:

1. Cocos_10m_grid_2010 (.ers, .sd, .xyz)
2. Cocos_50m_grid_2010 (.ers, .sd, .xyz)
3. Cocos_100m_grid_2010 (.ers, .sd, .xyz)
4. Cocos_250m_grid_2010 (.ers, .sd, .xyz)

and exist in ERMapper, ArcGrid, Fledermaus and ASCII xyz grid formats. A copy of the gridded files reside on the project unix disks /nas/pmd/bathy/grids along with other grids that have been produced by the Geophysical Analysis and Data Access (GADA) group. Appendix 2 provides the ANZLIC compliant metadata.

These sets of grids of the Cocos Island region are clearly an improvement on previously available grids. In comparison to those grids, the new grids:

- Show a high level of detail in the lagoon area of Cocos Island and the raised atoll.
- Show a good level of detail down the flanks of the raised atoll.
- Show the various islands in their correct spatial locations and in their correct form.

These grids are made up of many different data sets employing many technologies and sounding methods as well as coming from different eras in time. In terms of the reliability in both the navigation and the sounding the following ranking should be considered:

- Multibeam swath
- Singlebeam echosounder
- Naval charts
- Satellite derived bathymetry

However it should be noted that some old chart soundings may be accurate but the navigation not that certain. This may also apply to other older echosounder surveys. Modern multibeam and singlebeam echosounder data may be considered to be the most accurate both in terms of navigation and soundings. Many bathymetry surveys now claim navigation with an uncertainty to within 3 m while the sounding is to within 1 m. So in conclusion it may be assumed that the highest confidence in these grids can be placed in the regions of the grid where data has come from the newer multibeam and singlebeam surveys. In regions where data was sparse and heavily interpolated the final gridded bathymetry is only an indication of possible values there based on the nearest measured bathymetry.

The new Australian Bathymetry and Topography Grid (Whiteway, 2009) incorporated an earlier version of the 250 m grid created here for the Cocos Island region. This prototype used all the data available at the time which included singlebeam, multibeam and chart data. The resulting grid for the Cocos Island region is better than the previous version (Webster and Petkovic, 2005) but it uses the unreliable ETOPO1 to fill in unsurveyed areas.

It is envisaged that the new grids would be suitable for:

- Tsunami modelling
- Storm surge modelling
- Ocean and tide modelling
- Environmental impact studies
- Marine conservation
- Fisheries management
- Law of the sea territorial zoning

Possible future work may include detailed bathymetric mapping on the raised atoll region, and around North Keeling Island. As these are shallow water areas, the mapping should ideally be conducted with a high resolution system such as GA's EM3002 system, which is excellent to about 80m water depth and can map a swath over 200 m wide.

Only the 250 m grid is available for public release as part of the Australian Bathymetry and Topography Grid 2009 or as a dedicated Cocos (Keeling) Island grid from this work.

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Appendix 1

SATELLITE DATA PROCESSING

Method

A multi-spectral scene from the AVNIR2 sensor is 8-bit 4 band (Blue – 400 nm Green – 560 nm Red- 650 nm and NIR – 825 nm) with a ground pixel horizontal resolution of 10 m, acquired on the 9th March 2007 (figure 16), was used for this work. To convert the raw satellite data to reflectance data, a MODTRAN based atmospheric correction procedure was completed using the c-WOMBAT-c interface, (Brando and Dekker, 2003).

De-glinting; the removable of water-surface specular reflection was completed using a commonly used glint-correction technique for optical imagery which assumes a linear relationship across glinted and non-glinted pixels between each of the visible bands and the near-infrared (NIR), in optically deep water (Hochberg et al. 2003, Hedley et al. 2005). Land and exposed inter-tidal areas were masked from the imagery using a NIR threshold approach as show below:

- Intertidal Sand Flats – very elevated NIR indicates possibility of an exposed or partially exposed substrate
- Breaking Water - generally at the reef crest
- Deep Water – supervised classification based on known areas of optically deep water (greater then approx 25 m)

Depths were then derived through the application a physics-based bathymetry mapping technique: SAMBUCA (Semi-Analytical Model for Bathymetry, Un-mixing, and Concentration Assessment), which was developed in the ENVI/IDL environment as an objective and repeatable algorithm for extracting aquatic environmental information on a pixel-by-pixel basis from remote sensing data (Wettle & Brando, 2006) . It is based on the approach by Lee et al. (1998, 1999) for retrieving environmental variables from remote sensing data using an analytical model and optimization routine.

The basis of this approach is the expression of the subsurface remote sensing reflectance as a set of variables and a parameterization of this model to define it as a function of a set of environmental parameters. An optimization routine is used to minimize the difference/error between the measured subsurface remote sensing reflectance and the model by adjusting the variables and retrieving the environmental parameters, including water depth, that correspond to the lowest error. This process involves the use of a library of benthic substrate spectral signatures to determine, on a pixel-by-pixel basis, the ratio composition of any two substrates, eg 70% sand 30% coral. The library used in this project consisted of 3 common benthic substrates (sand, massive coral, seagrass) provided by the University of Queensland.

Quality Control

The optimisation process in SAMBUCA varies the environmental parameters associated with the water properties, depth and bottom substrate until the modelled spectra for each pixel is as close to the observed data as possible. Pixels where the error between the modelled and observed spectra is large indicate areas where the derived depth and other environmental variables may be considered more unreliable (Figure 28), and these were masked from the model as a quality control measure.

Tide and Datum Adjustment

The derived depths were adjusted for tide based on National Tidal Centre hourly data from the Cocos Island tide gauge (http://www.bom.gov.au/oceanography/projects/abslmp/data/index.shtml) and corrected to the Australian Height Datum (AHD) using the tide data and GA Seaframe Sensor Bench Mark datum information.

Validation / Accuracy Assessment

The derived depths were validated against Hydrographic Service chart data in the northern section of the lagoon, digitised as point data and overlaid on the 10 m horizontal resolution depth model.

Random samples of 1081 hydrographic chart points were selected, covering a variety of depths and substrates. Figure 26 shows the regression of the model depths against the validation data, with the high correlation coefficient of 0.82 and close fit of the regression line to the 1 to 1 line indicating a good modelling result.

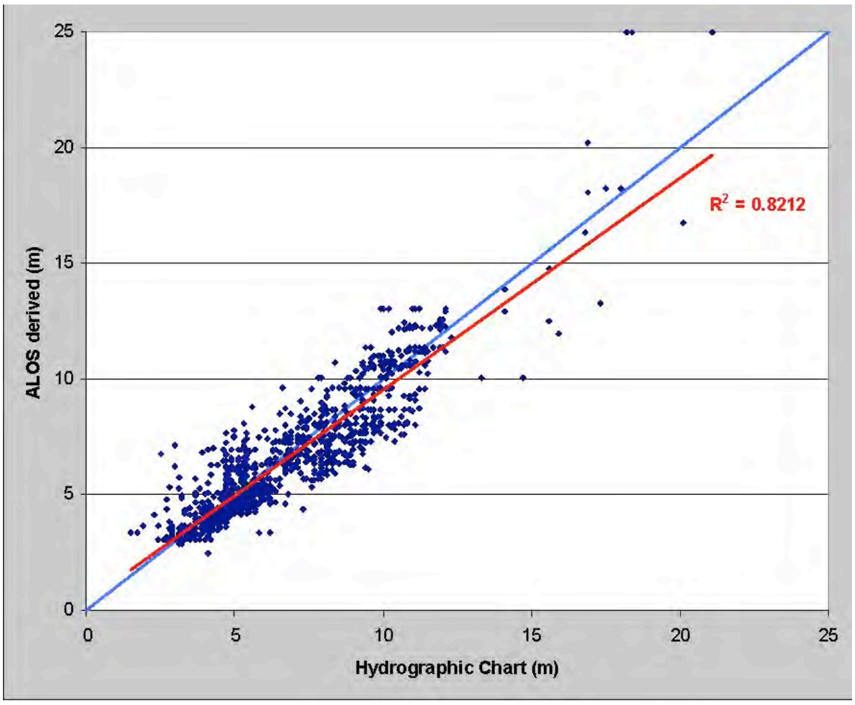

Figure 26*: Regression of ALOS derived depths versus Hydrographic chart data (regression: red, 1:1 line: blue).*

Analysis of the residuals of the modelled depths to the validation data indicates an average accuracy of within 12.3% of the validation depth at a 95% confidence level.

Georeferencing of data

An issue that may influence the validation results is the georeferencing of the hydrographic chart points and the ALOS scene. Both datasets were in a WGS84 UTM Zone 47S projection; however there was an observed horizontal offset of approx 30-40 m in some sections of the scene with near shore depth measures corresponding to land areas. This was corrected for by using the satellite image from the GEMD GIS which had been georeferenced to cadastre points. The following corrections were applied: x direction + 40 m, y direction + 30 m.

Issues noted in the derivation process

The following features and process issues were identified as delivering unreliable depth results, mostly identified by the examination of the model closure error (Figure 27). As indicated in the

'Quality Control' section of this appendix, due to the lower confidence in the depth estimate, no derived depths have been recorded in these pixels, which are shown only as part of the true-colour ALOS image in Figure 28.

Dark seagrass/algal substrates

Model closure was particularly poor over areas with a dark, low albedo substrate. These included areas close to the coasts of both West and South Islands (Figure 28 – Area B) and in the middle section of the lagoon stretching in an SW direction from Home Island (Figure 28 – Area A). These areas are described respectively by Williams (1994) as being 'Seagrass Sand and Silt Flats' and 'Algal-covered Staghorn Rubble'. In other words, both consisting of dark substrate materials (algae, silt) not included in the model spectral library. In addition, the description given of the Algal-covered Staghorn rubble section in the middle of the lagoon suggests a highly varied bathymetry where shadowing and the dark algae cover may have combined to adversely affect the closure of the model algorithm.

Deep holes in blue hole mosaic

The areas described by Williams (1994) as 'blue hole mosaics' stretch from the deep section of the central lagoon to the shallow flats near shore to South Island (Figure 28 – Area C). Model closure and depth determination in the depressions of these mosaics is variable, and may have been influenced by a number of factors including:

a) shadowing in the depressions by the hole rims
b) dark algal type substrates
c) high bioturbation and finer sediments at the bottom of the holes (Williams 1994)

Residual glint effects

In some pixels residual glint effects were observed after the glint correction process, which could create depth anomalies. This is most likely a result of there being a slight non-linearity in the relationship between the NIR and visible bands, possibly caused by the limited 8-bit radiometric resolution of the ALOS AVNIR2 data.

Metadata of the Depth Derived Dataset

Source Data

ALOS AVNIR2 4-Band Multi-spectral 8-bit
Scene ID ALAV2A059673840
Acquired 09032007 3:56 UTC

Projection

WGS84 UTM Zone 47S
10 m Horizontal Point spacing

Data File Format

Tab-delimitated ASCII (Easting, Northing, Depth), the data points are shown in figure 11.

Depth Point Codes

0: Land, 1: Intertidal / Reef Crest / Breaking Water, -100: No Depth Derived (closure error).

Tide & Datum Adjustment

Cocos Tide Gauge Reading (National Tidal Centre) 4:00 UTC - 0.87 m above tide gauge zero (TG0)
AHD offset to TG0 - 0.828 m. Adjustment of derived bathymetry to AHD - (-0.042 m)

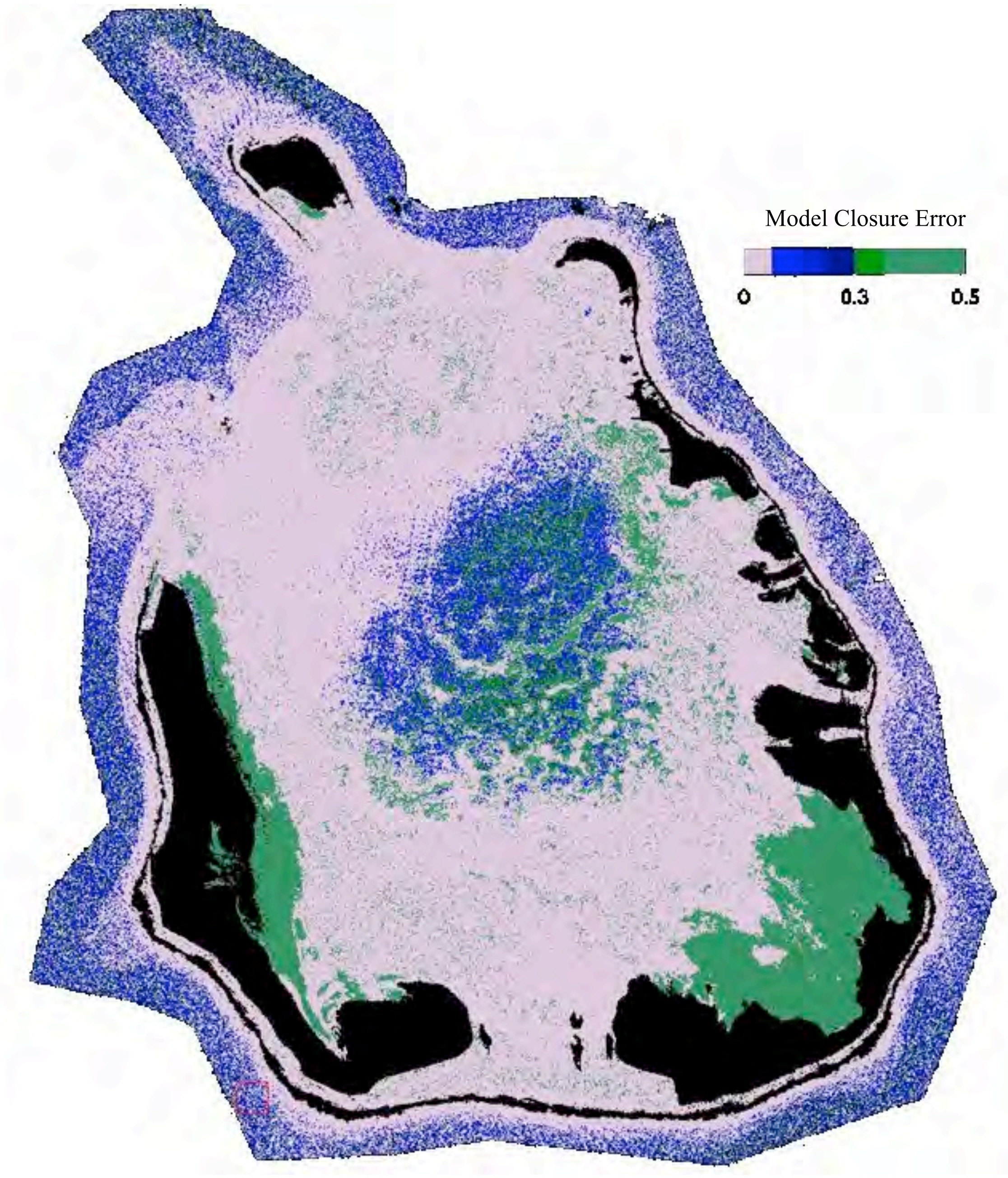

Figure 27: *SAMBUCA model closure error map of the Cocos (Keeling) Islands Main Atoll Spectral shape and magnitude closure error between modelled and observed data. Low values indicate good model closure. Values above 0.035 were considered unreliable for depth derivation (see Figure 28). Scale is the same as for Figure 28.*

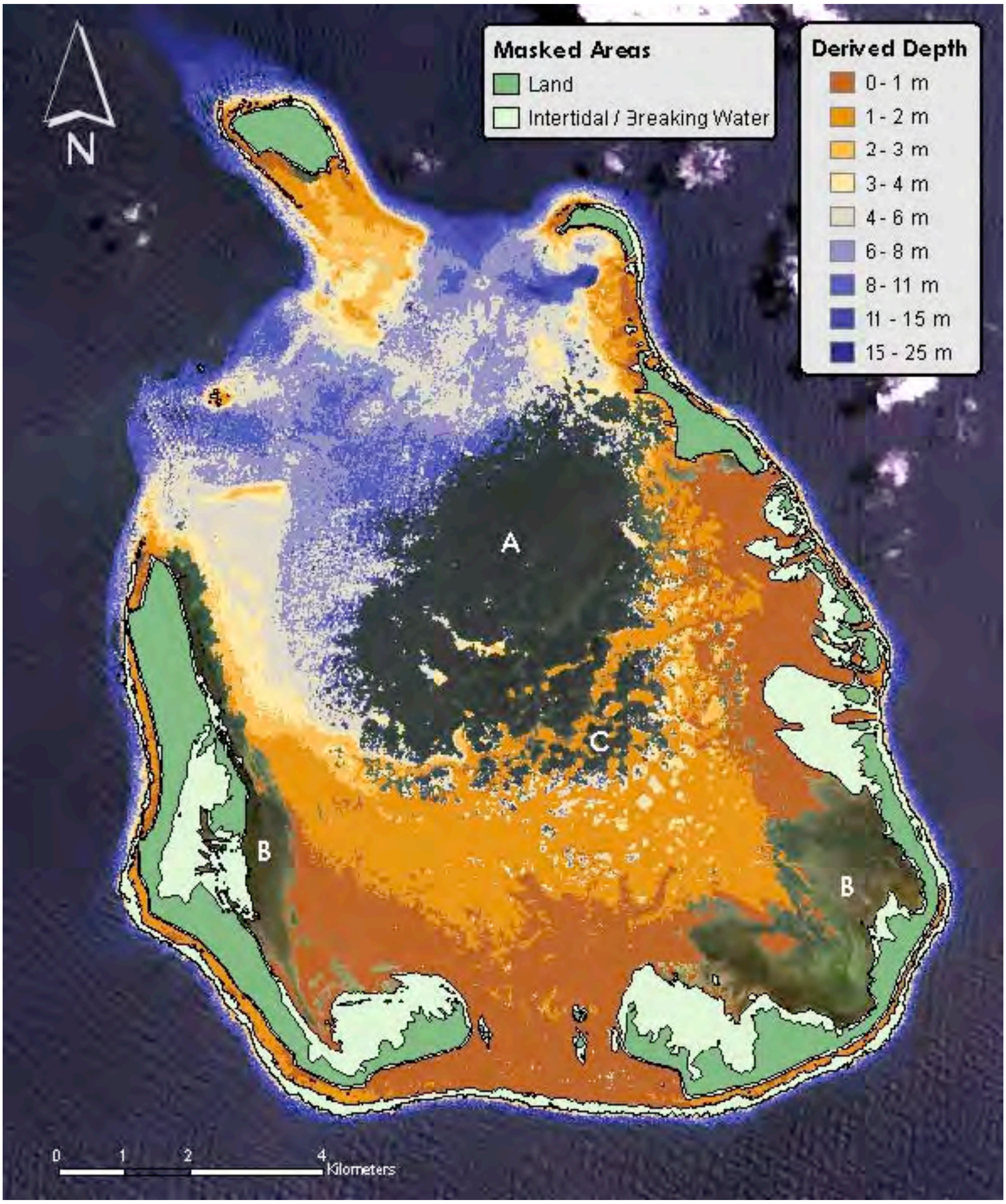

Figure 28: *Shallow Water Bathymetry of the Cocos (Keeling) Islands Main Atoll. Derived from ALOS AVNIR2 10 m resolution multi-spectral data. Note: Areas shown as the true-colour ALOS image indicate areas where model closure error was high and the derived depth could be considered unreliable. These include areas of dark algal and staghorn coral rubble substrate (A), dark seagrass/silt type substrate (B) and the 'blue-hole mosaic' (C).*

Appendix 2
ANZLIC METADATA RECORD

Metadata Element	Entry
ANZLIC Identifier	ANZCW0703013943
Title	High Resolution Bathymetry Grids of Cocos (Keeling) Island.
Custodian	Geoscience Australia
Jurisdiction	Australia
Abstract	Cocos (Keeling) Island is located approximately 3,685 almost due west of Darwin. It is a mid-ocean atoll with a coral reef, and a very shallow (1 – 20 m) shelf surrounds the island. Bathymetry data are required in this area to help identify major seabed processes and habitats. The data are also required to enable modelling of tsunami as they interact with the shelf around the island and the coast. Four new bathymetry grids have been created, including grids that integrate bathymetry with the island's topography.
Search Word(s)	GEOSCIENCES Geomorphology GEOSCIENCES Geophysics MARINE OCEANOGRAPHY Physical
Geographic Extent Polygon	95.5^0 -11.0^0, 98.0^0 -11.0^0, 98.0^0 -13.0^0, 95.5^0 -13.0^0
North Bounding Latitude	-11.0^0
South Bounding Latitude	-13.0^0
East Bounding Longitude	98.0^0
West Bounding Longitude	95.5^0
Beginning Date	2009-07-01
Ending Date	2010-06-31
Progress	Complete
Maintenance and Update Frequency	As Required
Stored Data Format	DIGITAL ER Mapper raster dataset, WGS84 Spheroid, WGS84 Datum
Available Format Type	DIGITAL - ER Mapper raster dataset, WGS84 Spheroid, WGS84 Datum DIGITAL - ARC/INFO 4 byte integer DIGITAL – Fledermaus SD file – ASCII X, Y, Z Grid File.
Access Constraint	Only the 250 m grid is available for public release.

Lineage	The grids are derived from data in Geoscience Australia's databases and recent sources which will eventually be entered into those databases. Satellite derived bathymetry was used in shallow waters. Two swath datasets acquired between 2003 and 2008 were used. Both surveys supply extensive regional coverage. A high quality coastline, as well as topography of Cocos and its islands were obtained from the GEMD GIS. Eleven singlebeam surveys from the GA MARDAT database. These data range in vintage from 1965 to 2000 and were edited to remove suspect datapoints, but were left uncorrected with regards speed of sound issues. Chart data from the AHS were used in both deep and shallow water. One singlebeam survey commissioned by DoTaRS that was previously unknown to GA was used.
Positional Accuracy	The grid incorporates data from surveys acquired since 1959. Modern surveys which use GPS have a positional accuracy of 5 - 30 m depending on several factors, while earlier surveys which used dead reckoning and Transit satellite fixes had positions accurate to 50 - 2000 m depending upon the water depth and strength of currents. These surveys overlap in an irregular distribution and the more extensive, higher quality swath datasets were used to mask data of lower quality and extent. Effectively there are two regions in the grid. One covered by multibeam data of high positional and bathymetric accuracy and the other heavily reliant on chart data and singlebeam surveys which are of lower positional and bathymetric accuracy. The grid cell sizes are 0.00225˚ (nominal 250 m), 0.0009˚ (nominal 100 m), 0.00045˚ (nominal 50 m) and 0.00009˚ (nominal 10 m).
Attribute Accuracy	The attribute accuracy varies depending upon the predominant data source in an area. Where modern, high quality swath bathymetric data that form an areal coverage exists, overlapping swaths and speed of sound corrections show that the data are quite accurate. For a significant portion of the region, predicted bathymetry from satellite data are the only source of data and the accuracy of these data are known to be good. No attempts have been made to compare bathymetry from high quality datasets to that which would be obtained from lesser data sets, although all the data exist to perform such a task.
Logical Consistency	Each of the input datasets were examined in detail and edited where necessary. Areas of poor navigation and obviously bad bathymetry were discarded. A hierarchical system was employed whereby the best and most extensive datasets replaced data of lesser datasets. All the various datasets were then brought together by the gridding algorithm (Intrepid – Desmond Fitzgerald Associates) and an ERMapper format grid produced.
Completeness	All of the known, available data (to 2010) were used in the production of the grids. The GA databases which underpin this grid will be updated as new surveys are completed and older surveys have corrections applied to them. A data density map was produced as a means of assessing the completeness of coverage and it could possibly be used as a variably opaque overlay of the bathymetric grid to highlight good quality areas and darken lesser quality areas.

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Metadata Date	2010-06-10
Additional Metadata	Mleczko, R., and Sagar, S., 2010. The Creation of High Resolution Bathymetry Grids for Cocos (Keeling) Island. Geoscience Australia Record 2010/38.