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The Creation Of High Resolution Bathymetry Grids for Christmas Island

Richard Mleczko

Record 2010/37

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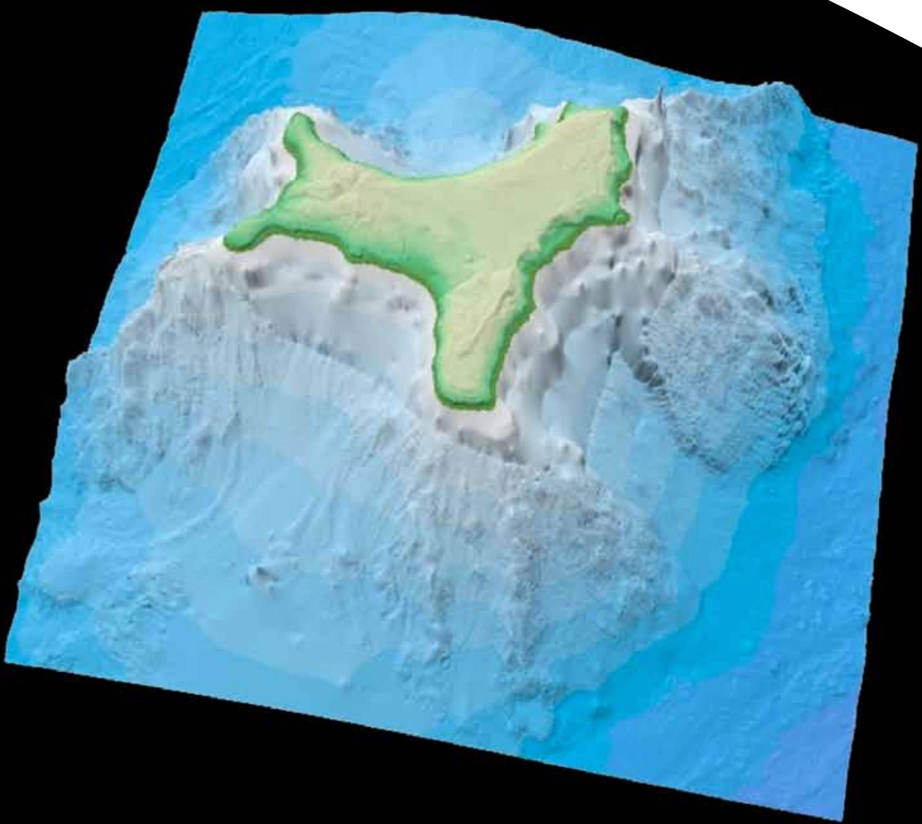

APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

The Creation of High Resolution Bathymetry Grids for Christmas Island

GEOSCIENCE AUSTRALIA
RECORD 2010/37

by

Richard Mleczko

Australian Government
Geoscience Australia

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Executive Summary

Christmas Island is located approximately 2,600 km north-west of Perth and is the surface expression of a tectonically uplifted emergent seamount. Bathymetry data are required in this area to help identify major seabed processes and habitats and to enable modelling of tsunami as they interact with the shelf around the coast of the island.

This report describes the methodology employed in creating detailed bathymetric grids of the Christmas 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.

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

1. Introduction

Christmas Island (10^0 29’ S, 105^0 38’ E) is an Australian territory with a population of about 2000 people. It is a raised limestone island which lies on oceanic crust approximately 1565 km north-west of Exmouth and 380 km south of Java. The island resembles a “T” with an area of 135 km^2 and is up to 20 km across. Christmas Island is in a tsunami-genic zone and therefore the first part of Australia to be affected by any disaster, making it a priority to hazard modellers.

Christmas Island is of significant importance to the scientific community with respect to coral reef development and plate tectonics. It has been the subject of studies such as tectonic uplift (Woodroffe, 1988), groundwater (Pettifer, 1976), seismic surveys (Exon, 1993), geology (Borissova, 2004), phosphate mining (Trueman, 1965), and conservation (Brewer, 2009). 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 Christmas Island tide gauge records. Hydrodynamic equations used in tsunami modelling in the far field are insensitive to small changes in the earthquake rupture 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 Christmas Island created by the Onshore Energy and Minerals Division (OEMD), (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 the 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 the immediate environment that surrounds the island, the Christmas Island seamount and the broader surrounding region. Maps of data distribution and three dimensional 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 Christmas Island region. However, one such dedicated grid was recently found. It was created by Geoscience Australia (GA) in 1994 but is no longer available in digital form. It is shown in Figure 1 and more details can be found in Borissova (1994). 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.

Subsets of four global or large regional grids are discussed in the following sections. All views in the figures are approximately 105^{o} to 106.5^{o} E and 10^{o} to 11^{o} S and have a vertical exaggeration of 6 times.

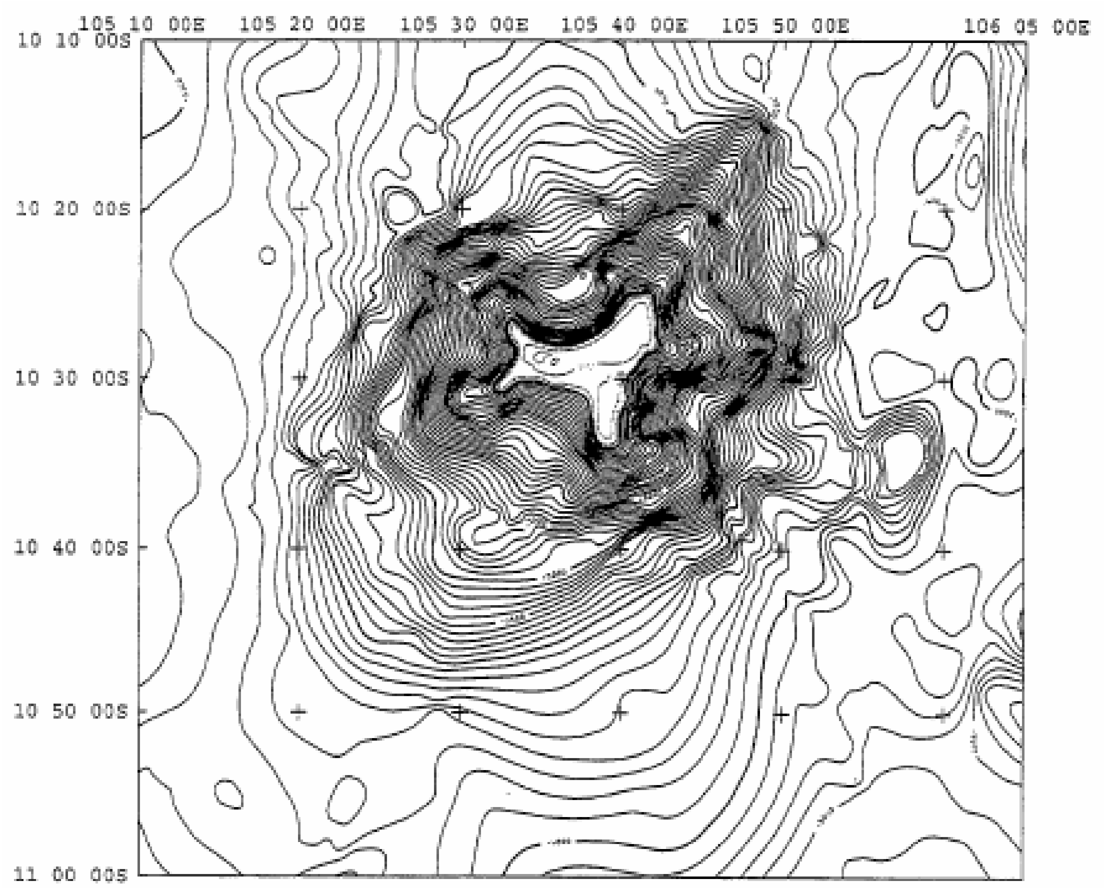


Figure 1: *The early Christmas Island grid from 1994.*

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 datasets and chart data from the Australian Hydrographic Service (AHS) was not included in the Christmas Island area. A full explanation of the datasets 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 Christmas Island region is shown in Figure 2.

Features of the Geoscience Australia 250 m grid in the Christmas Island region are:

- There is an erroneous 'reef ' just north of the island.
- There is an erroneous island just west of the main island.
- There is poor representation of the land.
- There is a wide shelf.

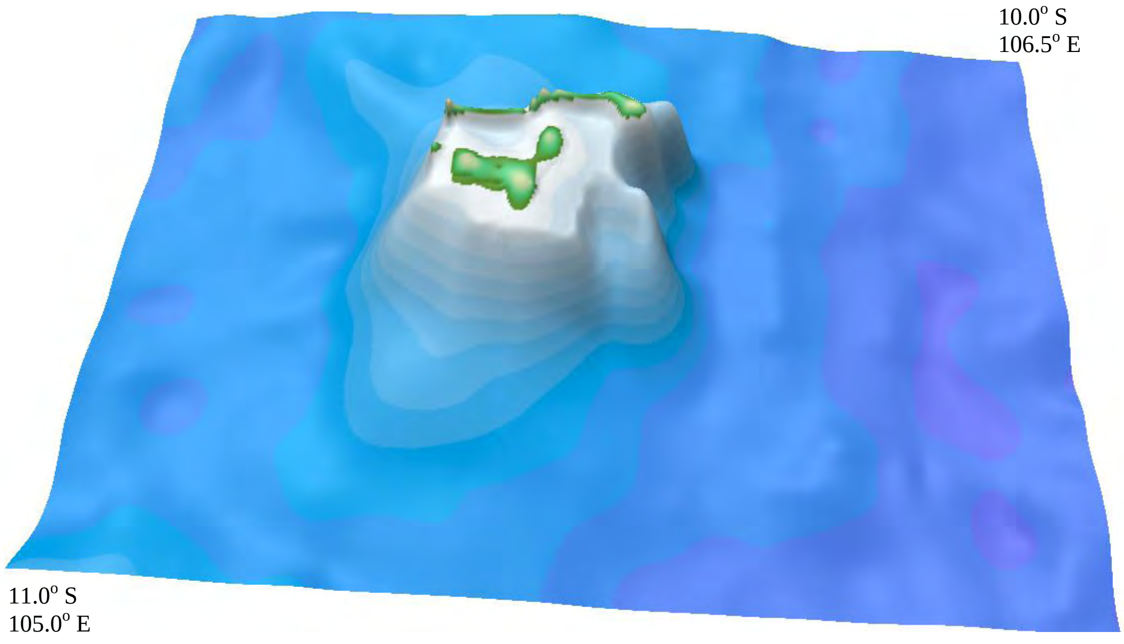


Figure 2: *The region around Christmas Island as represented by the GA Australian Bathymetry and Topography 9 second of arc grid 2005 (position marker approximate only).*

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 Christmas Island region is shown in Figure 3.

Features of the DBDB2 model for the Christmas Island region are:

- There is poor representation of the land.
- The grid lacks detail.

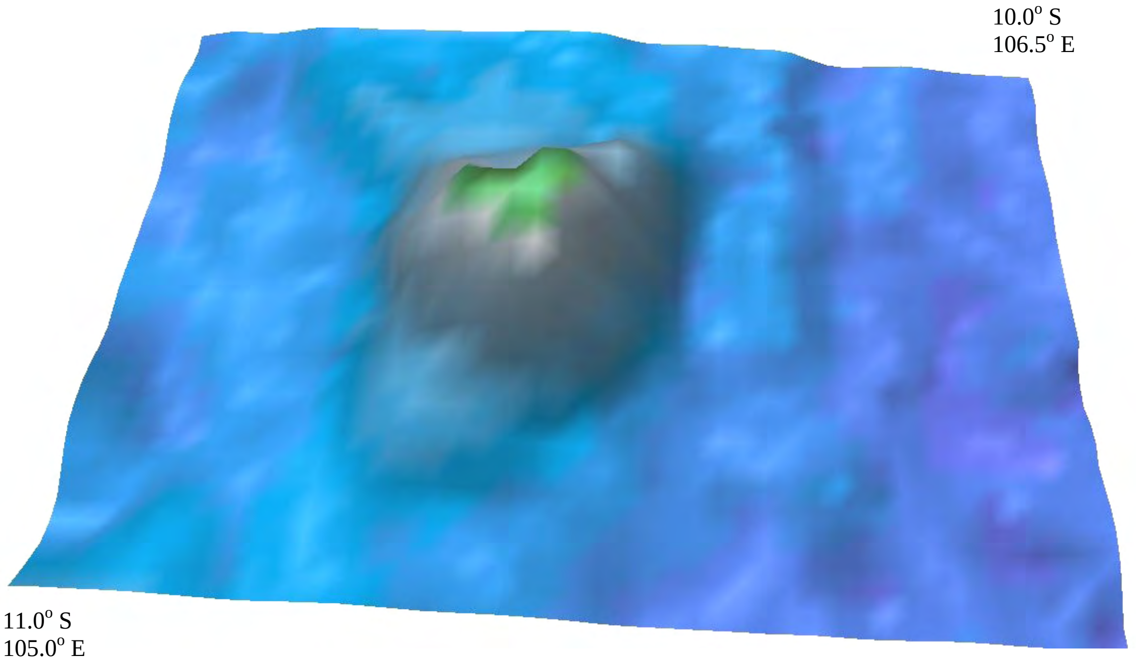


Figure 3: *The region around Christmas Island as represented by the DBDB2 2 minute of arc grid (position marker approximate only).*

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 is derived from sea-surface altimetry measurements, ocean soundings, Space Shuttle Radar Topography Mission 30 minute elevation data (SRTM30) and the 30 minute Global Topography dataset (GTOPO30). An extract of the model that covers the Christmas 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 dataset 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 Christmas Island region are:

- There is poor representation of the land.
- The grid lacks detail.

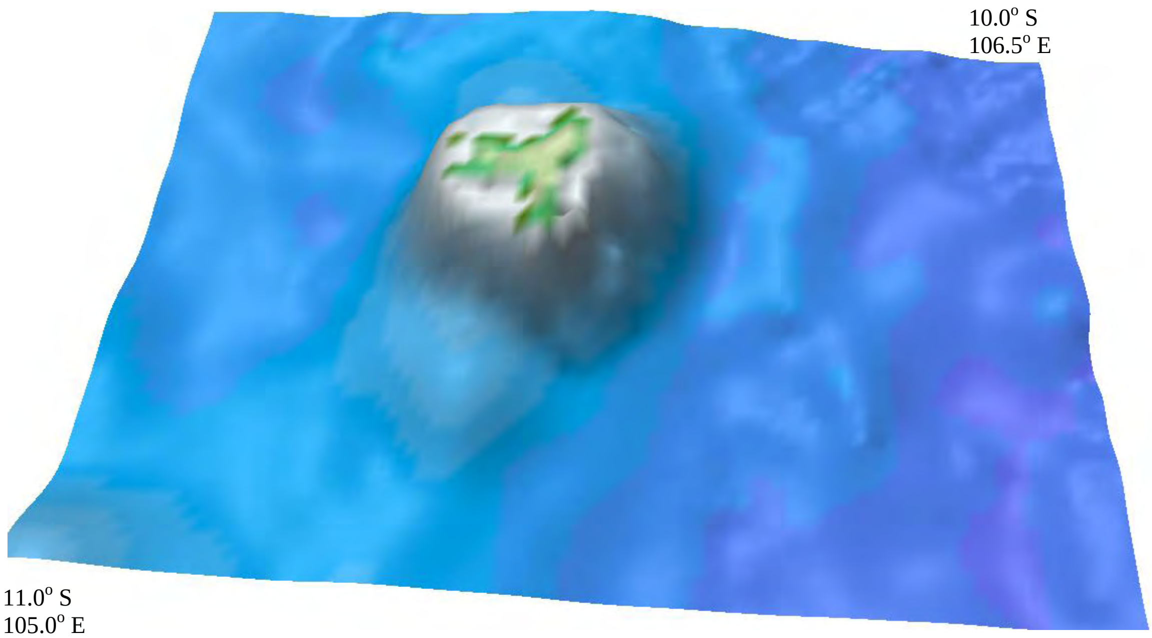


Figure 4: *The region around Christmas Island as represented by the ETOPO 1 minute of arc grid (position marker approximate only).*

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 Christmas Island region is shown in Figure 5.

Features of the GEBCO model for the Christmas Island region are:

- There is poor representation of the land.
- The grid lacks detail.

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

COMPARISON OF THE FOUR GRIDS

The Christmas 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 Christmas Island region by the four datasets include:

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

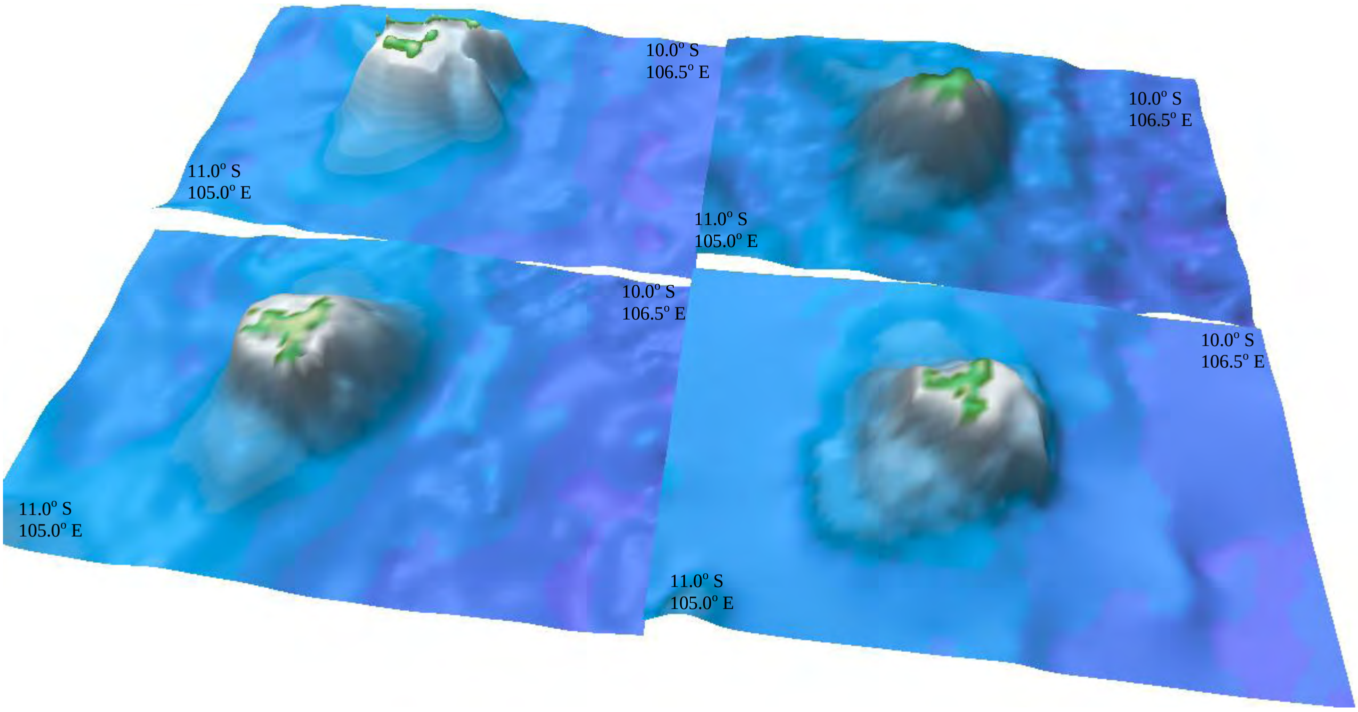


Figure 6: *Comparison of 4 widely used and popular bathymetry grids. Clockwise from the top left: the GA grid, DBDB2, GEBCO, and ETOPO1 (position markers approximate only).*

Dataset Discussion

What is evident from these four grids is the distinct lack of data density. The inconsistency in the shape and size of the shelf is of concern as well as the size of the land. The GA grid seems to be the better of the four grids in respect to the shape of the shelf mainly due to its higher resolution and the presence of more survey data. The ETOPO1 grid appears to be 150 m too shallow in most areas when compared to survey data for the area. None of these grids have the level of detail shown in the GA grid from 1994.

The purpose of this study is to improve on the Australian bathymetry grid with the inclusion of new bathymetry as well as topography and through a thorough assessment of the quality of the data employed.

3. Available Data

BATHYMETRIC DATA

A review of existing bathymetry data holdings at Geoscience Australia and a search for other bathymetry datasets that cover the Christmas Island region was required due to the low resolution of the available datasets. Only surveys that fell into the approximate region of 104^o to 107^o E and 9^o to 12^o S were considered (Table 1). Basically two data types were found: singlebeam echosounder, and multibeam echosounder (swath) .The history and characteristics of each dataset are described below.

Table 1: Christmas Island region bathymetry

SURVEY NAME	VESSEL NAME	DATA TYPE	SOURCE INSTITUTION*
"AHS Chart" fairsheet barcodes are as follows: 100004048, 100004049, 100004050, 100004051, 1000013391 and 1000022729.	Unknown navy vessels	chart	AHS
Sonne 199	R/V Sonne	multibeam	BGR
FR09/95	R/V Franklin	echosounder	CSIRO
FR07/96	R/V Franklin	echosounder	CSIRO
FR09/00	R/V Franklin	echosounder	CSIRO
GA 107	R/V Rig Seismic	echosounder	GA
GA 2476	R/V Sonne	multibeam	GA
Christmas Island	M/V Sealand	echosounder	DoTaRS
MR04K03 Leg 2	R/V Mirai	multibeam	JAMSTEC
DSDP22GC	D/V Glomar Challenger	echosounder	NGDC
KH7202	R/V Hakuho Maru	echosounder	NGDC
ODP123JR	R/V Joides Resolution	echosounder	NGDC
UM69	R/V Umitaka Maru	echosounder	NGDC
V3308	M/V Vema	echosounder	NGDC
VIT31A	M/V Vityaz	echosounder	NGDC
WI343815	USNS Wilkes	echosounder	NGDC

*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, JAMSTEC= Japanese Agency for Marine Science and Technology,NGDC= National Geophysical Data Center.

Australian Hydrographic Service data

The Australian Hydrographic Service (AHS) acquires and maintains a large collection of bathymetric data for the purpose 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 AUS608 and fairsheet survey class SD004. Contour lines were digitised from chart AUS608 for this work to improve the density of near shore data and stabilise the gridding process. It is noted that the accuracy of these contour lines is probably poor. For areas near Flying fish Cove and Norris Point the AUS920 chart was digitised for this work. The distribution of the chart data is shown in Figure 7.

All datasets have been converted to mean sea level (MSL) and WGS84. The points can be found on chart AUS608: http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus608&subchart=0. The charts state that data closer to Christmas Island was collected from 1964 to 1972, and that data further away was collected in 1984. For very near to shore the data points can be found on chart AUS920: http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus920&subchart=1 and data are of the vintage 1958 to 1964. The horizontal positional accuracies are stated as anywhere from 5 m to 500 m.

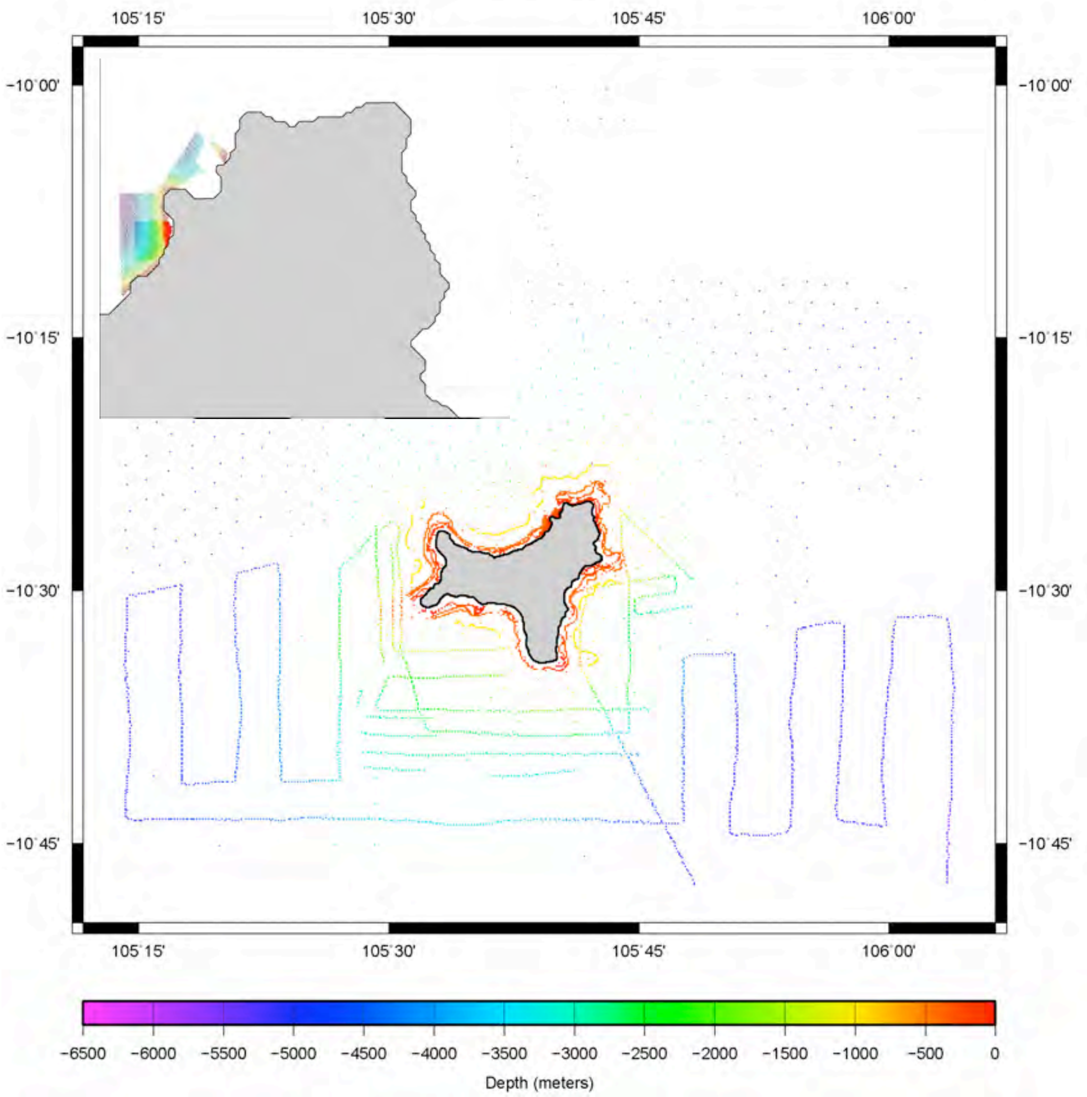


Figure 7: *AHS chart data exhibiting the highest densities at Flying Fish Cove and Smith Point (shown inset, colour scale -650 m to 0 m).*

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 two R/V *Sonne* surveys undertaken in the Christmas Island region and these are 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 Christmas Island. As more data were 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 were immediately sent to GA at the conclusion of the survey.

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

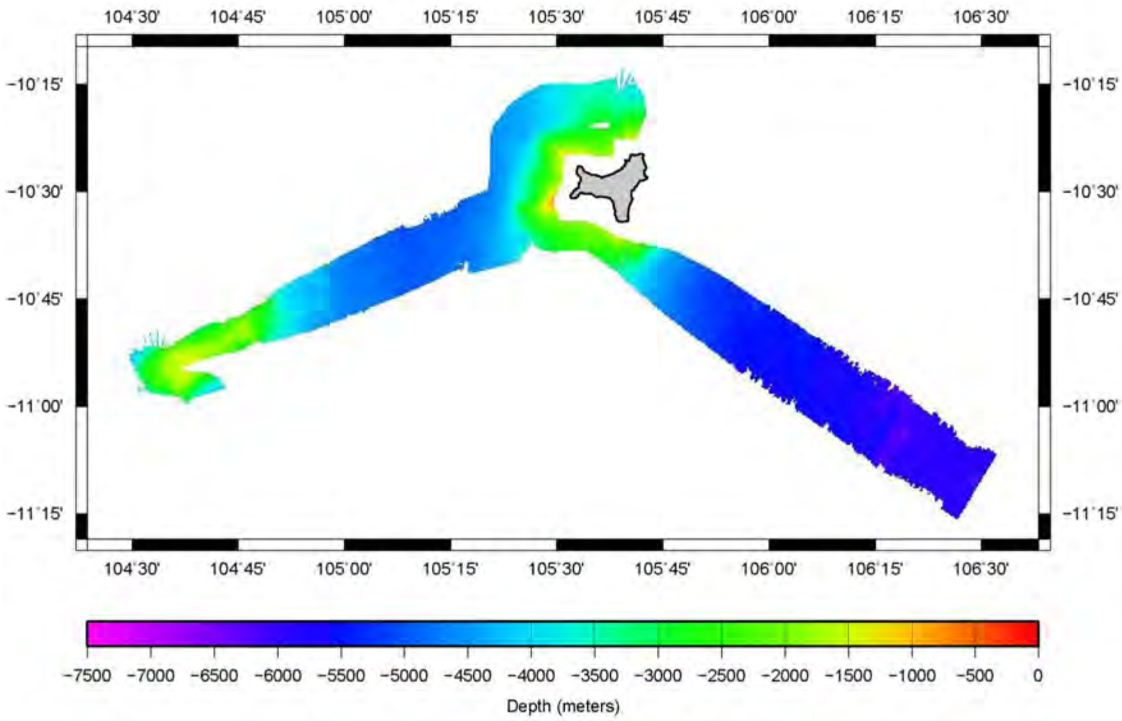


Figure 8: *Sonne 199 data showing high resolution in deep water.*

Marine National Facility surveys

The Marine National Facility is managed by the CSIRO. The CSIRO has collected data around Christmas 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 sampled at one minute intervals. For surveys of this vintage GPS would have been used with a positional accuracy of 100 m. More information can be found at: http://www.marine.csiro.au/nationalfacility/, on the National Facility website. The data distribution is shown in Figure 9.

FR08/1995

The R/V *Franklin* visited the area in 1995. More details on this survey can be found at the following link: http://www.marine.csiro.au/marq/edd_search.Browse_Citation?txtSession=4754.

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.

FR09/2000

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

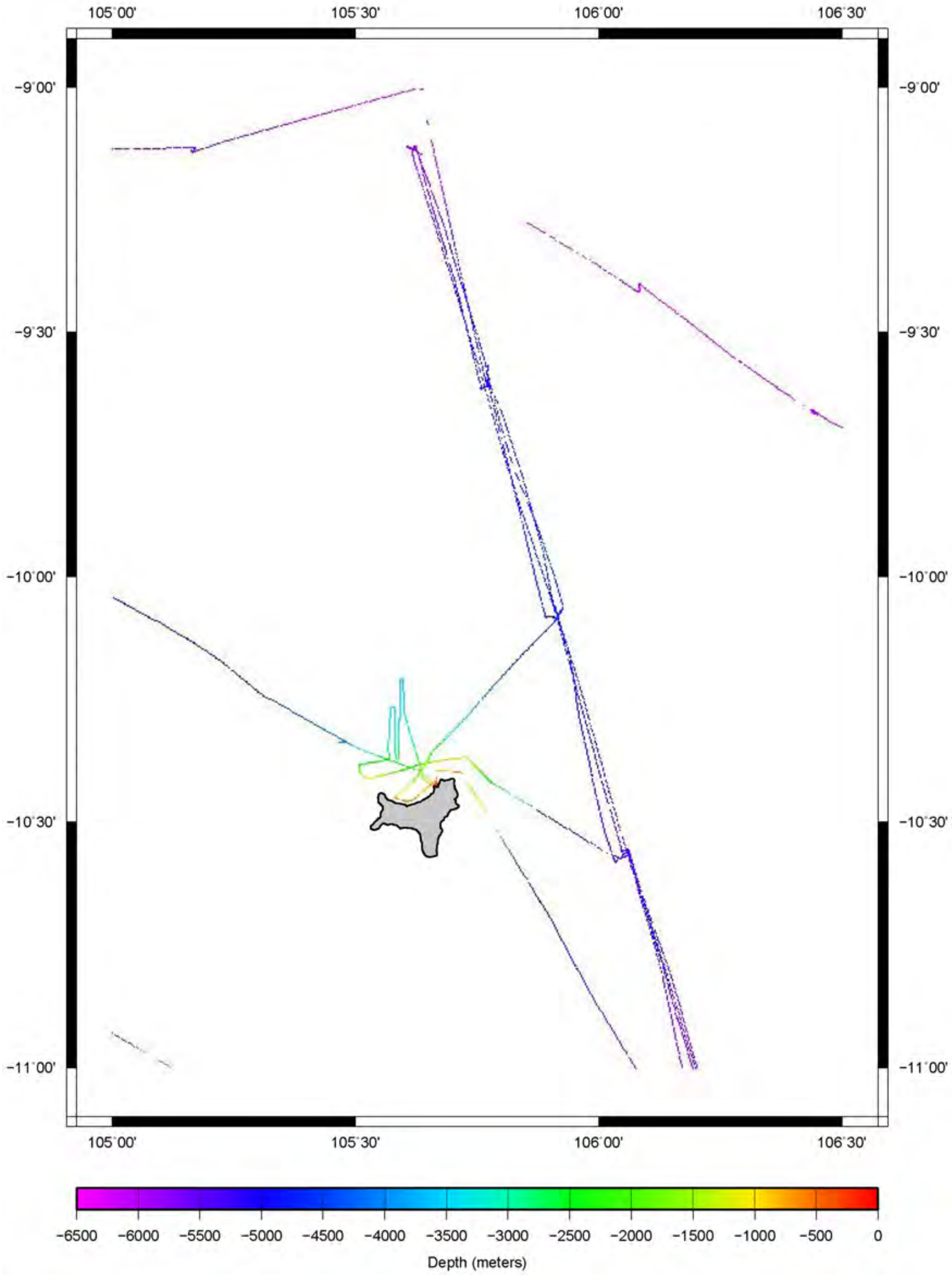


Figure 9: *R/V Franklin data; showing that most data are in deeper water.*

Department of Transport and Regional Services (DoTaRS) data

In 2002, a company called *Sea and Land Surveying* was commissioned by DoTaRS to survey three locations around Christmas Island as shown in Figure 10. The three surveys: Flying Fish Cove Hydrographic Survey, Smith's Point Hydrographic Survey and the Proposed East Coast Port Hydrographic Survey were conducted from the 3rd to the 13th of June 2002. The navigation used was GPS with a positional accuracy of 2 to 5 m. A survey report has been requested from the surveyor. Contact details are given in the references under *Shepherd.* This data complements what was collected by the AHS (Figure 7 inset).

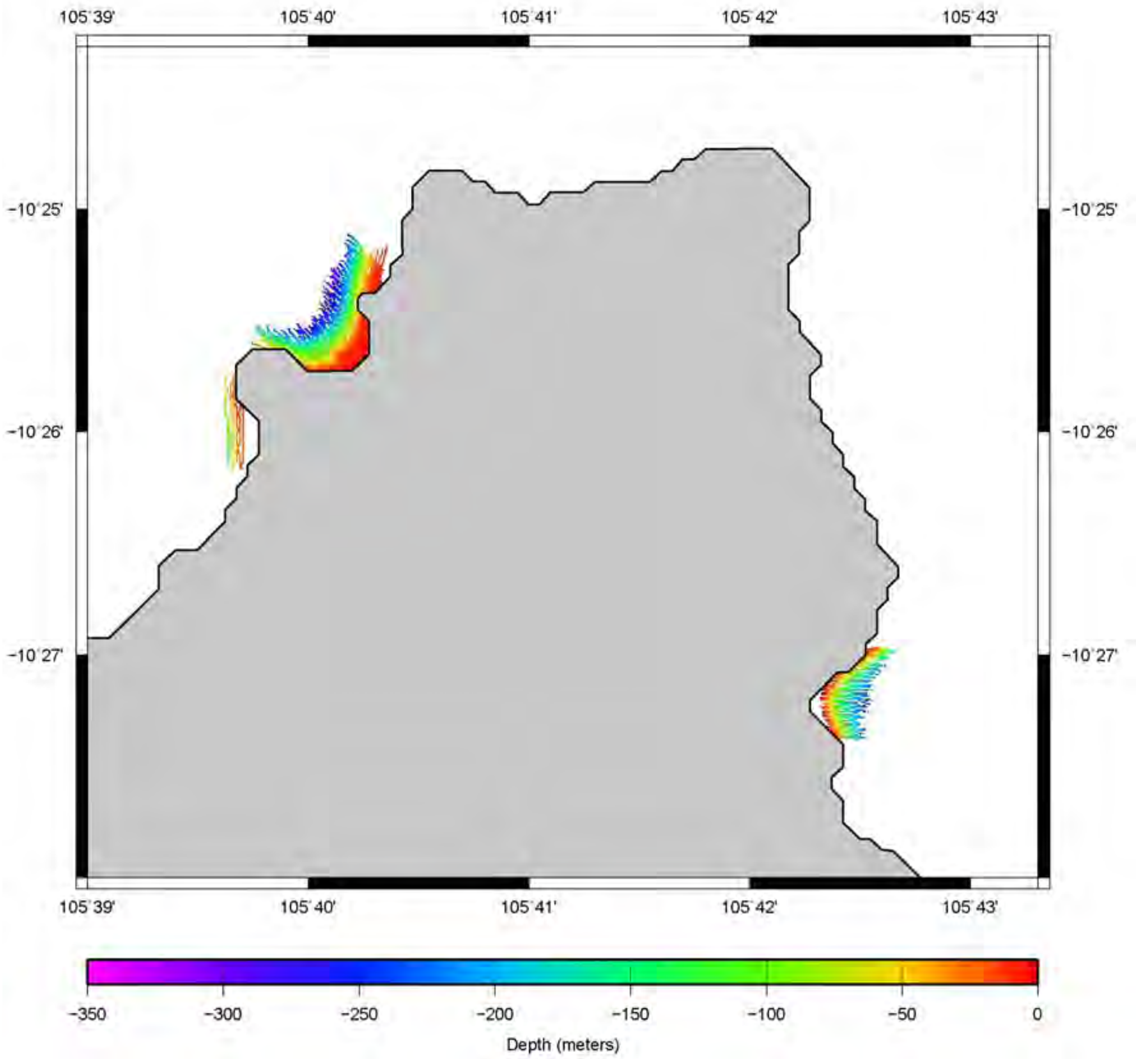


Figure 10: *DoTaRS data showing high density in the bays.*

Geoscience Australia data

GA owns datasets from two surveys around Christmas Island, one of them being swath. The surveys are discussed in more detail in the next section.

GA 107

In 1992 the R/V *Rig Seismic* surveyed around the Christmas Island region. The data are shown in Figure 11. DGPS backed up by transit satellite and sonar Doppler was used as the navigation system with an accuracy of no worse than 30 m. More details on this survey can be found in Exon et al (1993).

GA 2476

In 2008 the R/V *Sonne* collected swath bathymetry in the Christmas Island region. The navigation was GPS with an accuracy of 2 to 5 m. More information on this survey can be obtained from the cruise report by Gravionic (2008). The data distribution is shown in Figure 12.

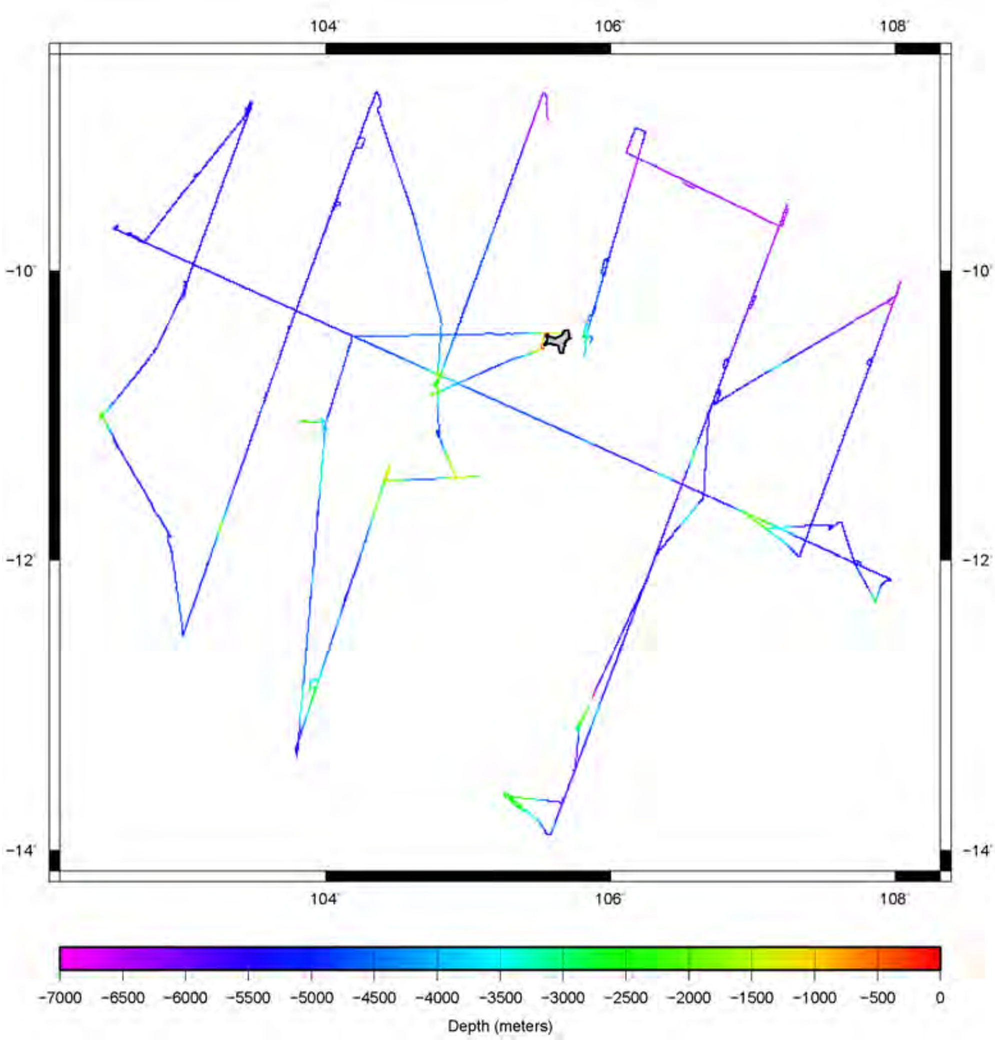


Figure 11: *Rig Seismic survey 107 (more data shown than used).*

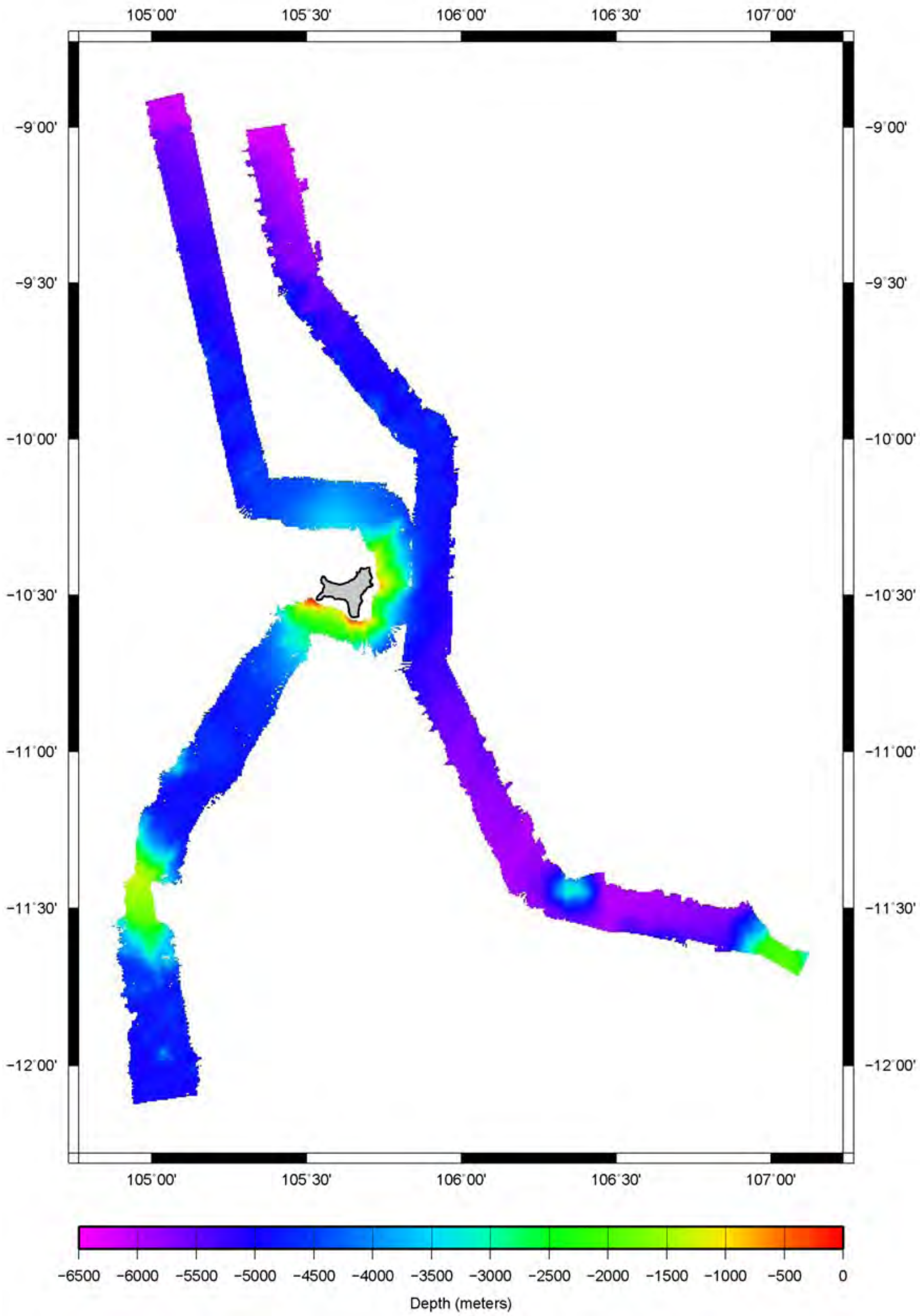


Figure 12: *R/V Sonne survey (GA2476) data showing swath very close to the island.*

Japanese Agency for Marine Science and Technology (JAMSTEC) data

JAMSTEC is the Japanese agency for marine-earth science and technology. It has a fleet of many vessels and more information (http://www.jamstec.go.jp/e/index.html) can be found from the website.

MR04-03 Leg 2

In 2004 the R/V *Mirai* surveyed just north of Christmas Island. The navigation used was GPS with accuracy in the vicinity of 2 to 5 m. The horizontal accuracy stated for the swath was 1 m. Details on the survey can be found from Ueki et al (2004). The data are shown in Figure 13.

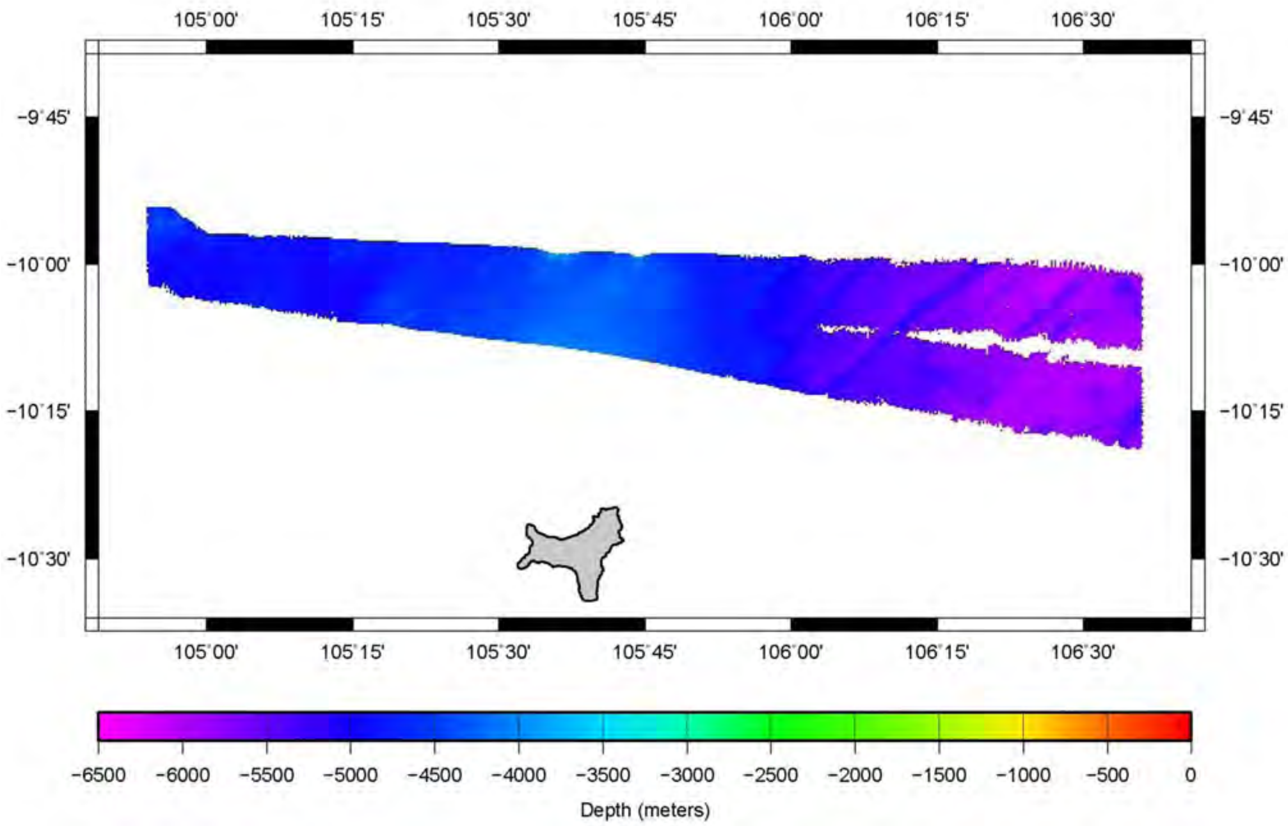


Figure 13: *R/V Mirai survey data showing data were collected in very deep water only.*

National Geophysical Data Center (NGDC)

The National Oceanic and Atmospheric Administration (NOAA) maintain a web site that is home to the National Geophysical Data Center (NGDC). It can be found at: http://www.ngdc.noaa.gov/. When compiling data to be gridded it is always worth checking the NGDC as its database holds bathymetry from all over the world. Seven surveys were found from the NGDC that were conducted in the Christmas Island region and they are discussed below. The data are shown in Figure 14.

DSDP22GC

In 1972 the *Glomar challenger* sailed past the south of Christmas Island. The transit satellite system was used for navigation with horizontal accuracy in the vicinity of 500 to 1500 m. More details on (http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=DSDP22GC&t=102697&s=6&d=7) this survey can be found at the link.

KH7201

In 1972 the Japanese vessel the *Hakuho Maru* surveyed to the east of Christmas Island. The navigation system is not given in the records but given the vintage it is assumed that the transit satellite system was used with accuracy in the vicinity of 500 to 1500 m. More details on this survey: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=KH7201&t=102697&s=6&d=7, can be found at the link.

ODP123JR

In 1988 the R/V *Joides Resolution* was transiting past the east coast of Christmas Island with the echosounder turned on. The transit satellite system was used for navigation with horizontal accuracy of 500 to 1500 m. More details on this survey can be found at the following link to the NGDC: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=ODP123JR&t=102697&s=6&d=7.

UM69

In 1969 the Japanese vessel the *Umitaka Maru* surveyed to the east of Christmas Island. No navigation system is stated for this survey, but given the vintage it is assumed that the transit satellite system was used with an accuracy of 500 to 1500 m. More details on this survey can be found at: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=UM69&t=102697&s=6&d=7.

V3308

In 1976 the R/V *Vema* was transiting past the east coast of Christmas Island. The transit satellite system was used for navigation together with the sextant with an overall horizontal accuracy in the vicinity of 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.

VIT31A

In 1959 the Russian vessel the M/V *Vityaz* was transiting past the east coast of Christmas Island. The sextant was used for navigation with a horizontal accuracy of 3,500 to 10,000 m. More details (http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=VIT31A&t=102697&s=6&d=7) can be found at the link.

WI343815

In 1978 the USNS *Wilkes* was transiting past the east coast of Christmas Island with the echosounder turned on. The transit satellite system was used for navigation with a horizontal accuracy of 500 to 1500 m. More details on this survey can be found at the following link to the NGDC: http://www.ngdc.noaa.gov/idb/struts/results?op_0=eq&v_0=WI343815&t=102697&s=6&d=7.

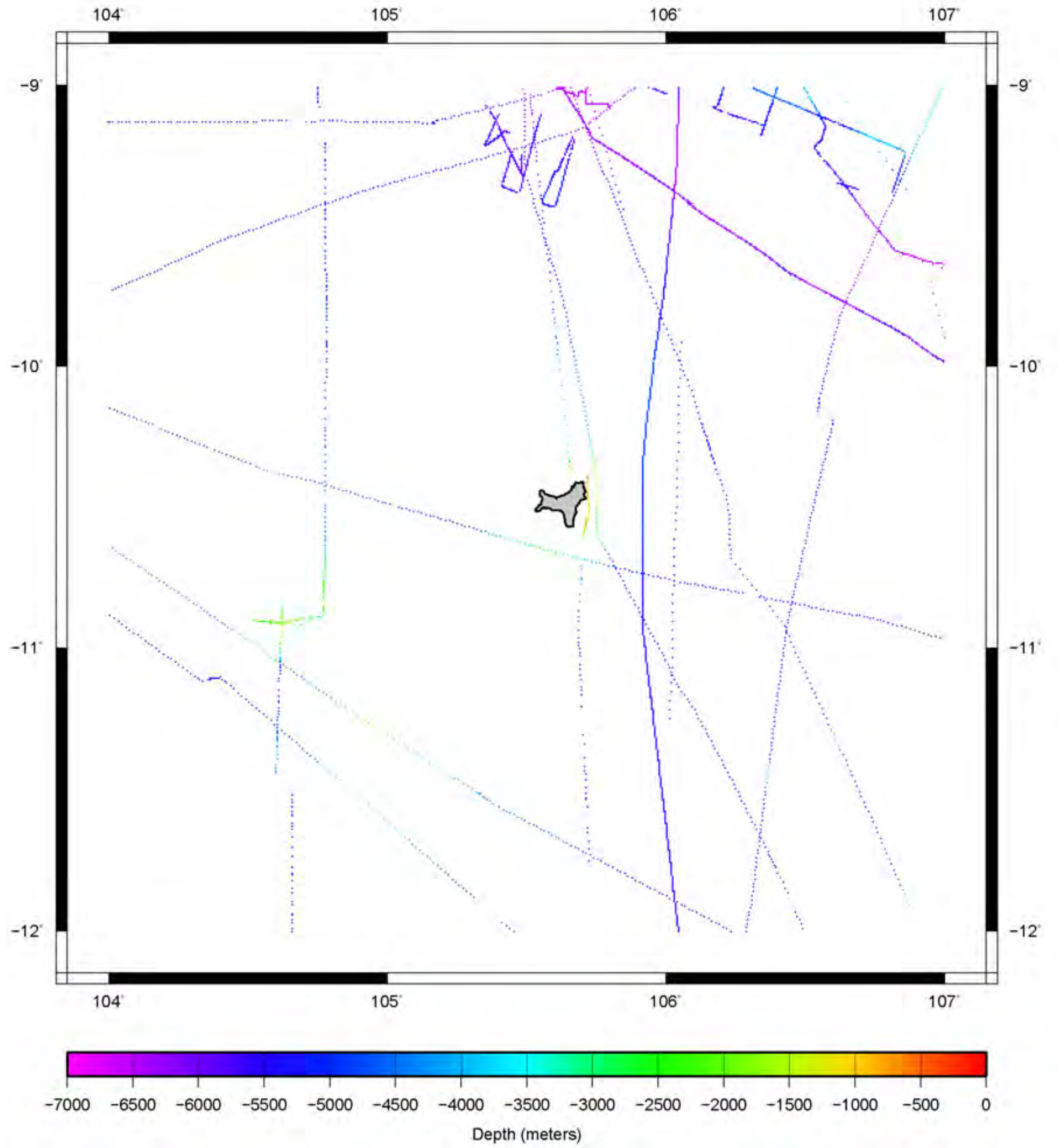


Figure 14: *NGDC data (more data shown than used).*

TOPOGRAPHIC DATA

The four publicly available bathymetric grids of the Christmas 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 datasets were evaluated (Table 2).

The Onshore Energy and Minerals Division (OEMD) provided two very high resolution grid datasets taken from their GIS of Christmas Island (see Porritt 2006). The first dataset is a 5 m DEM of the entire island and the second is in the form of 1 m airborne laser readings. The data sources and characteristics are shown in Table 2.

Table 2: Christmas Island topography.

NAME	RESOLUTION	SOURCE INSTITUTION
Christmas Island DEM	5 metres	Geoscience Australia
Airborne Laser elevation	1 metre	Geoscience Australia

DEM

Topography data were obtained from the OEMD and the 5 m resolution data are shown in Figure 15. For a description of what data went into creating this DEM, please see Porritt (2006).

Laser Elevation

The method of airborne laser soundings is discussed in detail in Porritt (2006). As explained in the reference the final processed data were turned into a series of 1 m DEM tiles covering the east of the island only. The tile covering Flying Fish Cove was used to produce a 3 metre grid for use in tsunami modelling. This grid is not shown or discussed in this report. Other tiles covering the east of Christmas Island are available for any future high resolution modelling. There are plans by the OEMD to collect laser soundings for the west of Christmas Island. The 1 m DEM is shown in Figure 16.

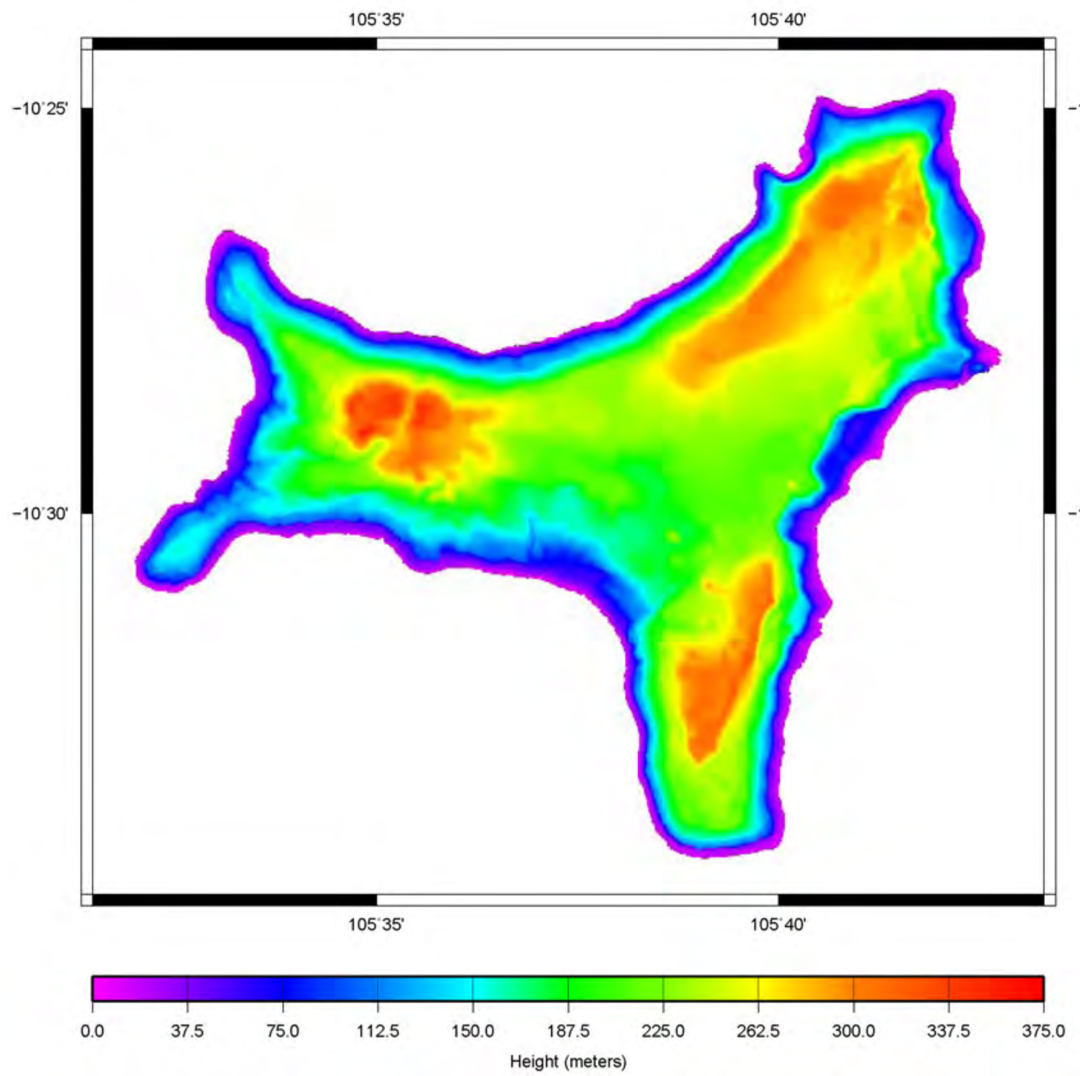


Figure 15: *Christmas Island 5 m DEM.*

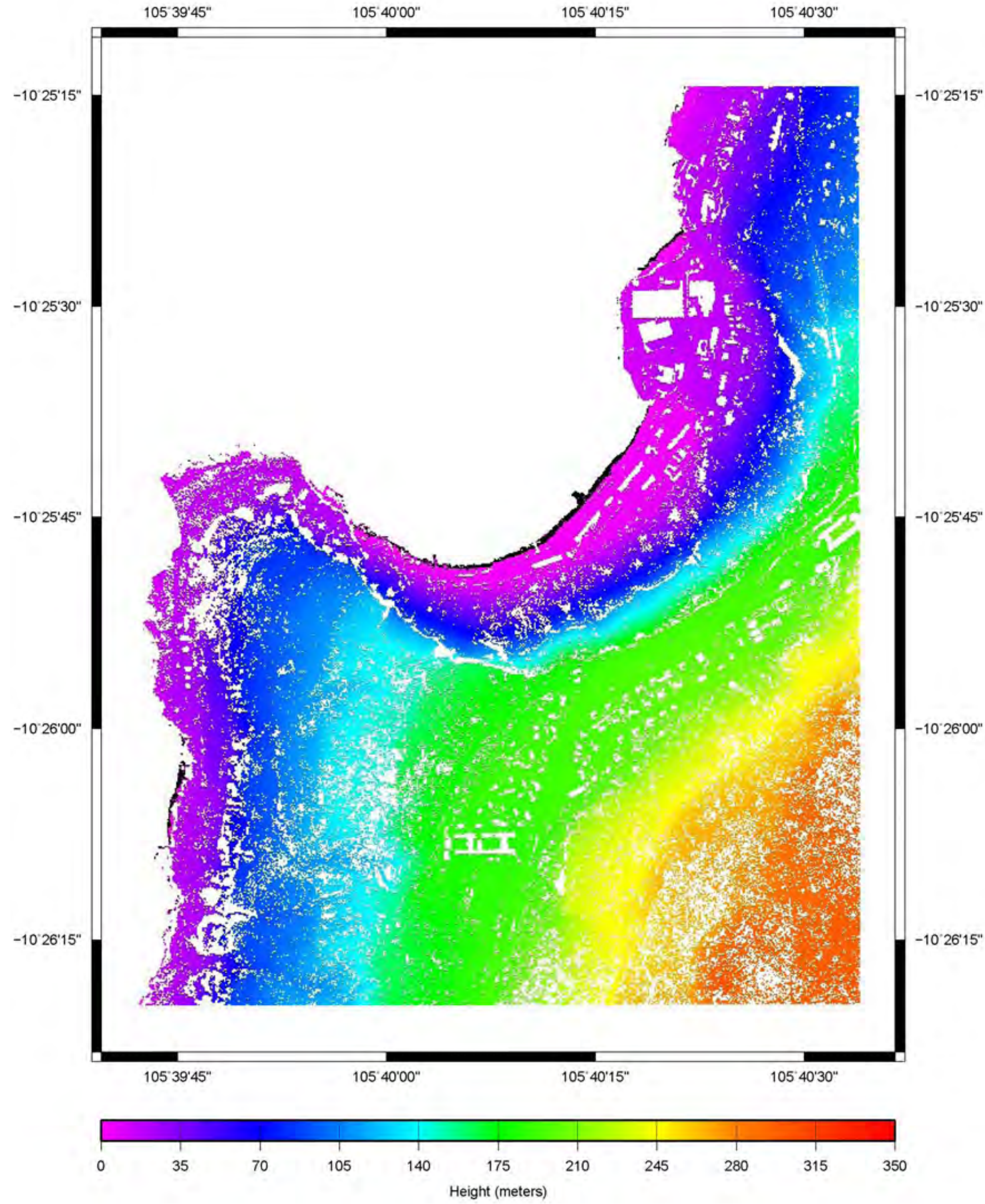


Figure 16: *Flying Fish Cove 1 m laser elevation.*

OTHER DATA

Charts and Images

Though naval charts, satellite images and aerial photography are not part of the dataset 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 AUS608 obtained from the AHS (under the MOU) (http://www.hydro.gov.au/webapps/jsp/charts/charts.jsp?chart=Aus608&subchart=0) was used and is shown in Figure 18. Satellite imagery which was obtained from the Christmas Island GIS and which had superior geo-referencing than the chart was also used and is shown in Figure 17.

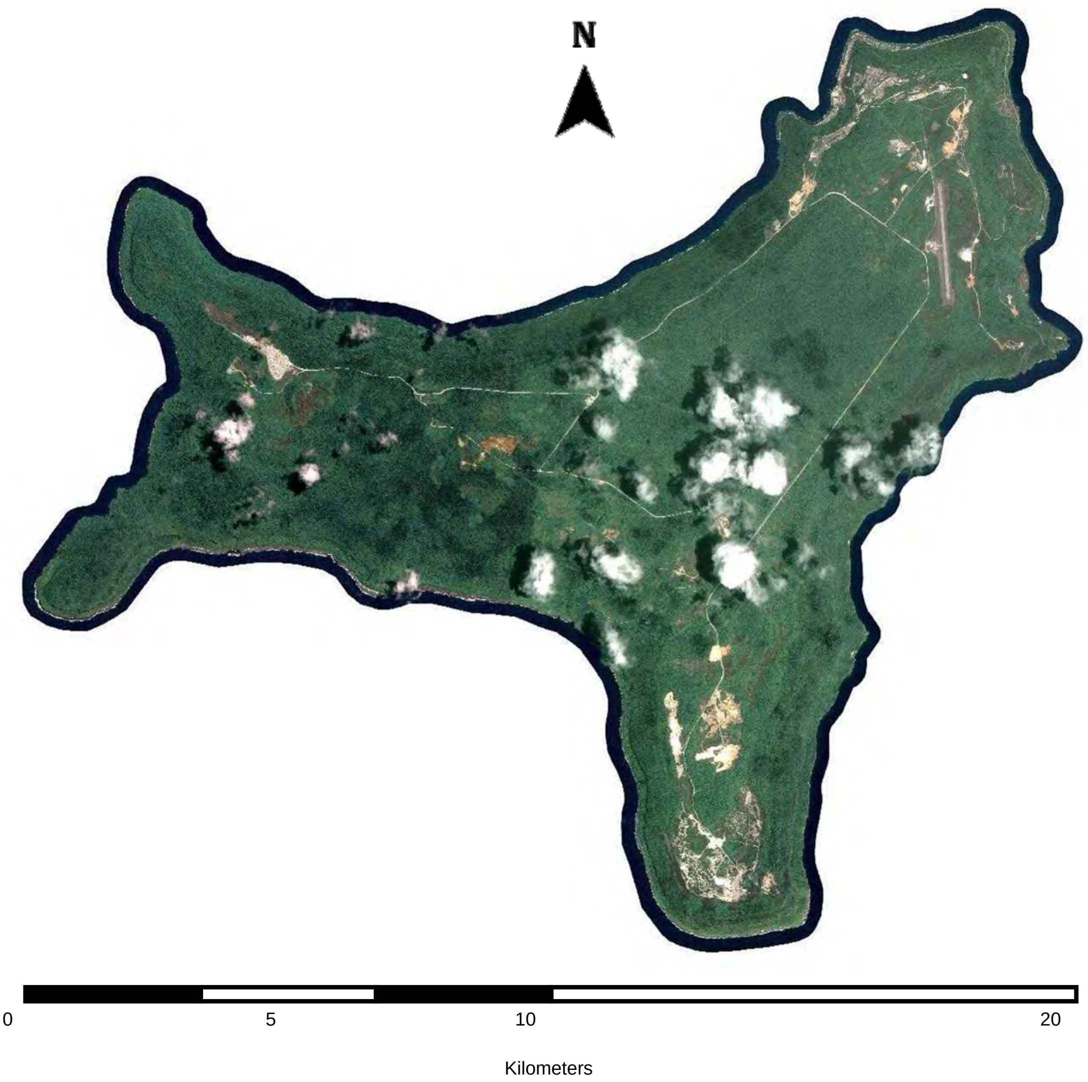
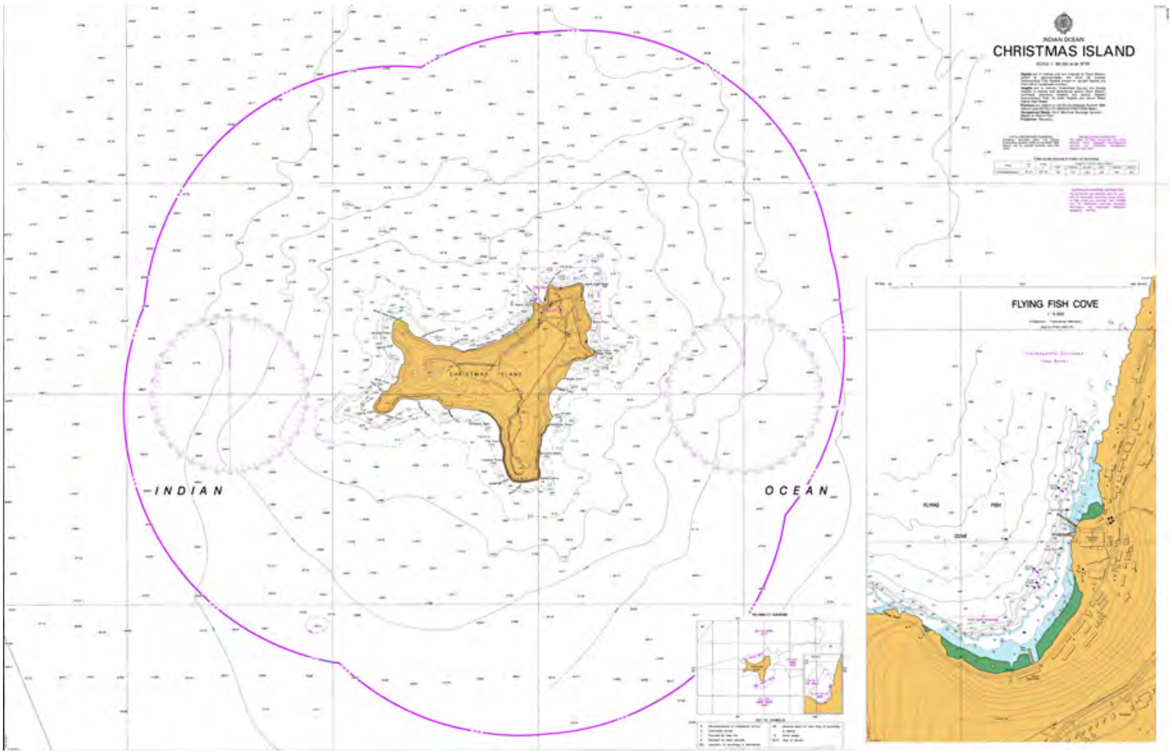


Figure 17: *Satellite image (used with permission OEMD).*



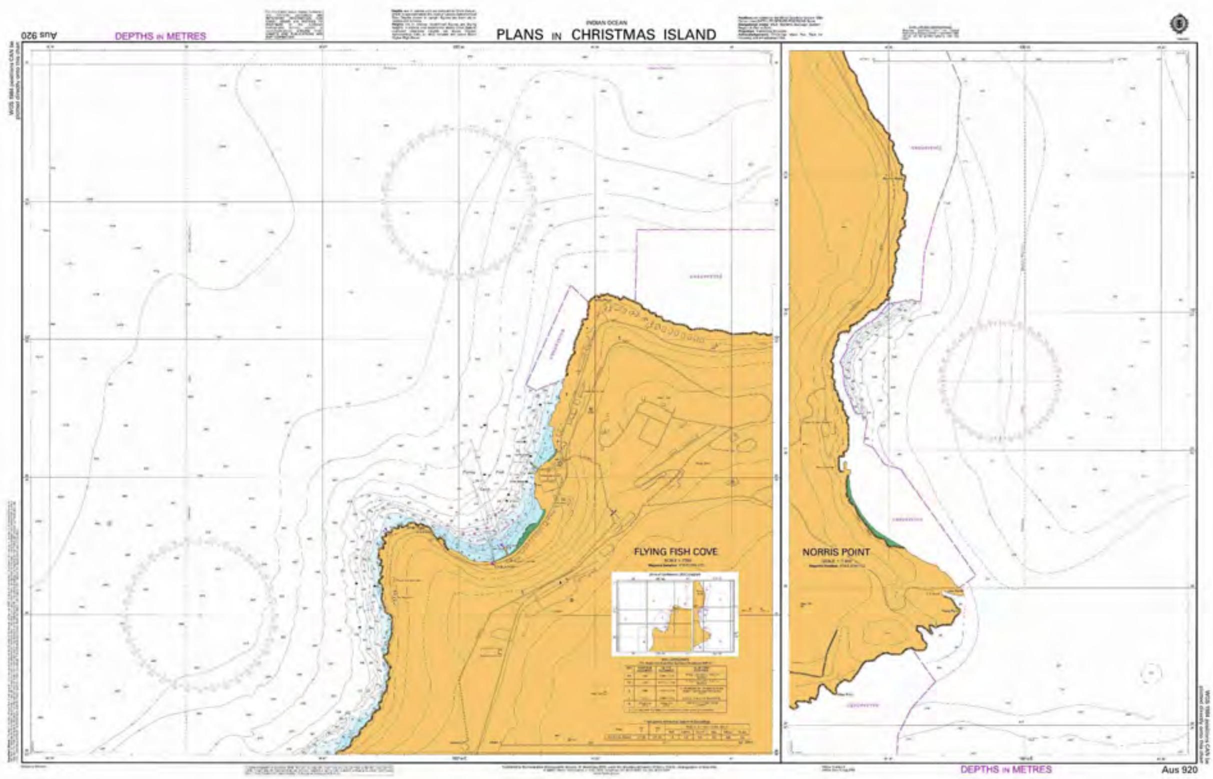


***Figure 18**: Charts AUS608 (top) and AUS920 (used under licence AHS, not to be used for navigation).*

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 making a valid gridded surface. As a first step, all datasets were converted to the WGS84 datum and if possible the depths were referenced to mean sea level (MSL). 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 were so large, the data were internally gridded within CARIS and exported as an 80 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 (0.9 metre) correction was applied to correct them to mean sea level.

5. Analysis and QC of Bathymetric Data

The fully processed datasets 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 datasets 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 were then exported in ASCII xyz format ready to be gridded.

PROCEDURE

All final processed datasets were loaded into ArcMap, except for the swath data where only a geo-TIFF 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 some 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.

It is important to realise that 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 of the surface 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 dataset consult Marks and Smith (2005).

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

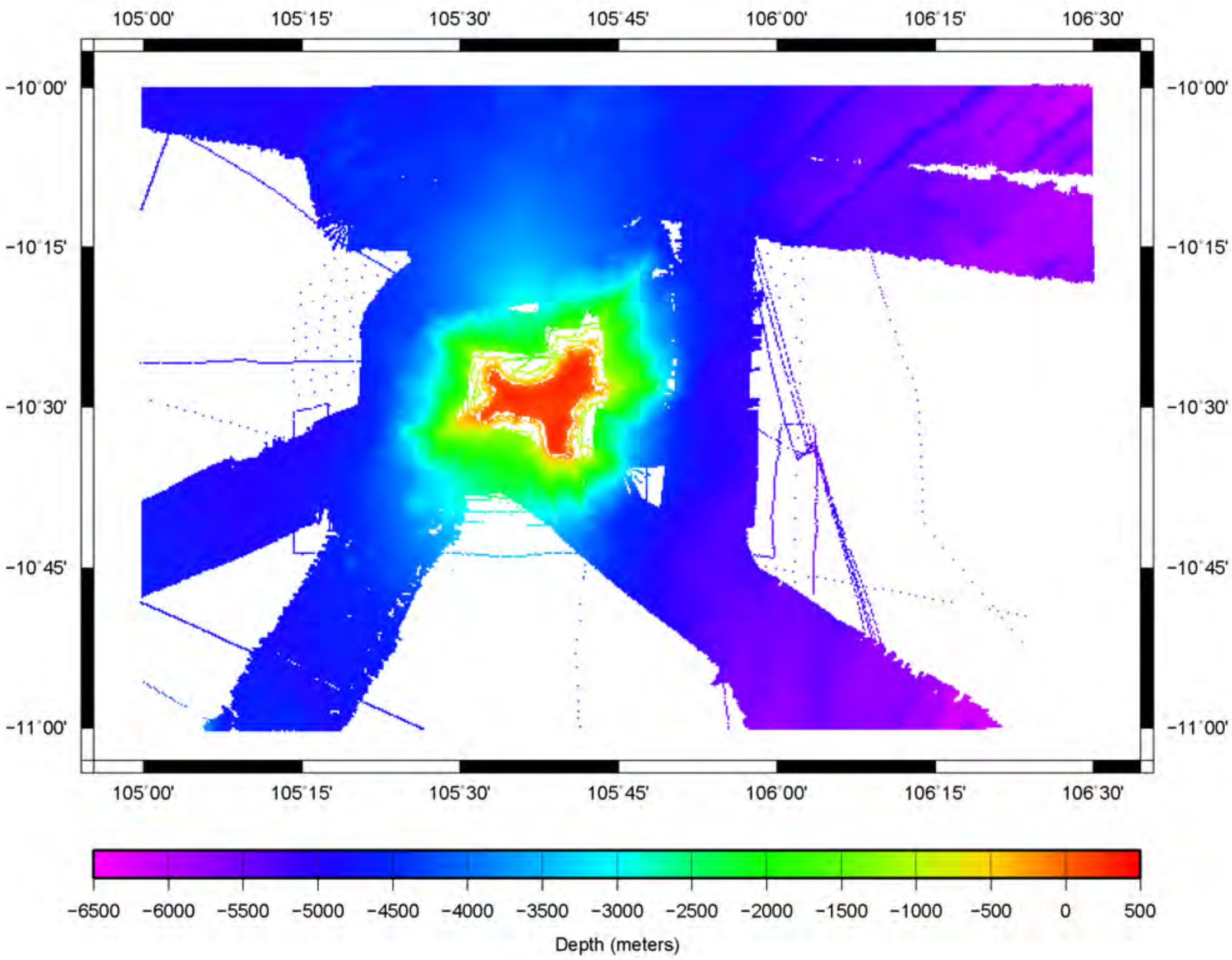


Figure 19: *The final dataset illustrates the data density.*

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 dataset. In an area such as Christmas 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 density may not support it.

Table 3: Data density

SURVEY NAME	DATA TYPE	DURING ACQUISITION	AS USED IN THIS WORK
Shallow Bay Region			
Christmas Island Hydrographic Survey	echosounder	0.5 – 1.5 m	0.5 – 1.5 m
“AHS Chart inner”	chart	unknown	15 m
Deep Water			
Sonne 199	multibeam	20 - 50 m	80 m
Sonne GA2476	multibeam	5 - 200 m	80 m
MR04K03 Leg 2	multibeam	80 m	80 m
FR09/95	echosounder	unknown	170 m
KH7202	echosounder	unknown	200 m
GA 107	echosounder	unknown	300 m
FR07/96	echosounder	unknown	350 m
FR09/00	echosounder	unknown	350 m
VIT31A	echosounder	Unknown	500 m
DSDP22GC	echosounder	unknown	1400 m
V3308	echosounder	unknown	1500 m
ODP123JR	echosounder	unknown	1600 m
WI343815	echosounder	unknown	2600 m
“AHS Chart outer”	chart	unknown	3000 m
UM69	echosounder	unknown	3500 m

For the singlebeam datasets 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 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 island.

A decision was made to produce five grids. A fine scaled grid with a 10 m cell size was seen as possible in three bays of the island. A 50 m cell size grid would be suitable over the rise area surrounding Christmas Island, whilst a 100 m cell size grid would be appropriate for further out. 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 (80 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.

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 in case cells contained interpolated data that seemed unrealistic.

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.

Christmas Island Regional 250 metre grid

The Christmas 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 one gridding artefact was detected. There is a slight mismatch in gradient moving from the near-shore sparse chart data to the high density swath data. This can be seen as a join which circles the entire island. However, the grid is still a significant improvement of any grid so far at this resolution. When compared with the GA grid from 1994 both grids share similar features. However a detailed comparison is not possible as the 1994 grid no longer exists in digital form. Figure 25 shows a profile across the Christmas Island region.

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

PARAMETER	VALUE
Latitude range	-11^{o} to -10^{o}
Longitude range	105^{o} to 106.5^{o}
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	2000 cells

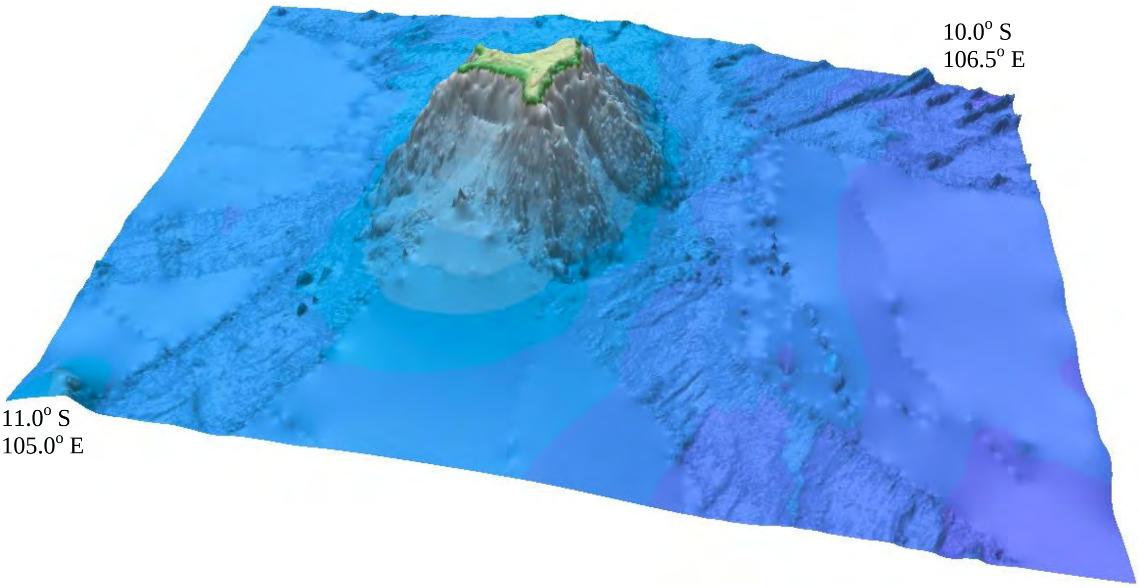


Figure 20: *The Christmas Island regional 250 m grid 2010 from this work (6 times vertical exaggeration, position marker approximate only).*

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Christmas Island 100 metre grid

The higher resolution grid is shown in Figure 21. It uses all 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 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 the join mentioned in the previous grid is still present.

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

PARAMETER	VALUE
Latitude range	-10.75° to -10.15°
Longitude range	105.25° to 106.09°
Cell size	0.0009 degrees (~3 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2000
Maximum residual	0.01 m
Extrapolation limit	2000 cells

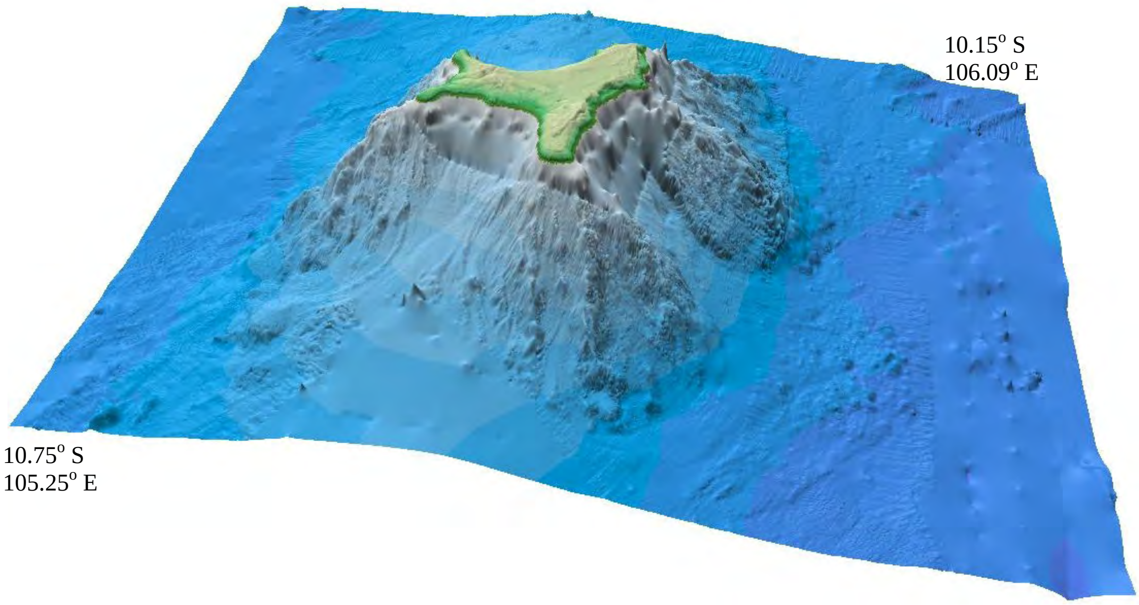

Figure 21: *The Christmas Island 100 m grid (4 times vertical exaggeration, position marker approximate only).*

Christmas Island 50 metre grid

An 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 emergent seamount and a grid at this scale is probably unique. All the original data were honoured and the join mentioned in the previous grid is still present.

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

PARAMETER	VALUE
Latitude range	-10.7° to -10.25°
Longitude range	105.4° to 105.9°
Cell size	0.00045 degrees (~1.5 sec of arc)
Cell assignment	Nearest neighbour
Minimum curvature tension	0.5
Maximum iterations	2000
Maximum residual	0.01 m
Extrapolation limit	2000 cells

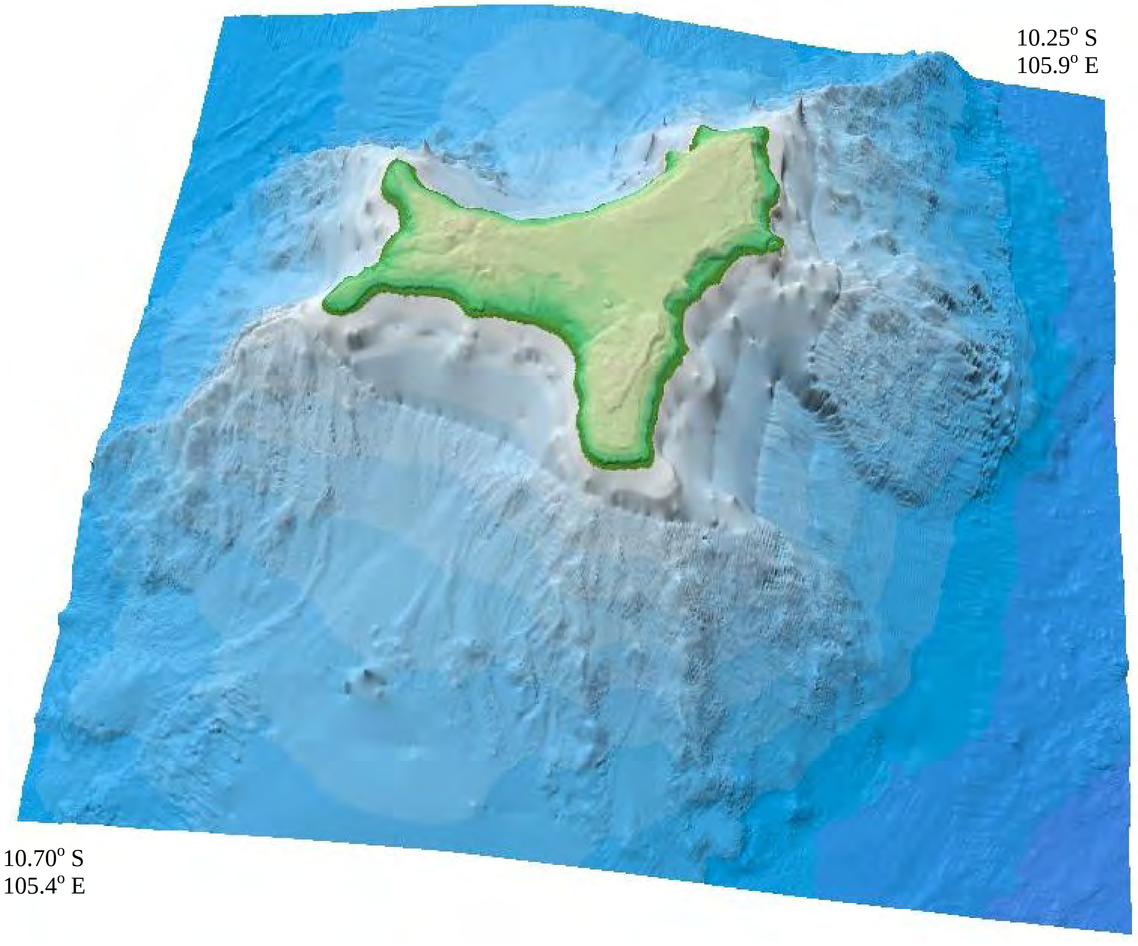

Figure 22: *The Christmas Island 50 m grid (4 times vertical exaggeration, position marker approximate only).*

Christmas Island bays gridded at 10 metres

Two extremely high resolution grids showing smaller regions around Christmas Island are shown in Figures 23 and 24. The computational parameters used in Intrepid are shown in Table 7. The grid on this scale is supported by both the bathymetry and topography data and it is probably the first time that these bays have been gridded. All the original data were honoured and no gridding artefacts were detected.

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

PARAMETER	VALUE
Latitude range	-10.45° to -10.40° / -10.46° to -10.45°
Longitude range	105.65° to 105.67° / 105.70° to 105.72°
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	2000 cells

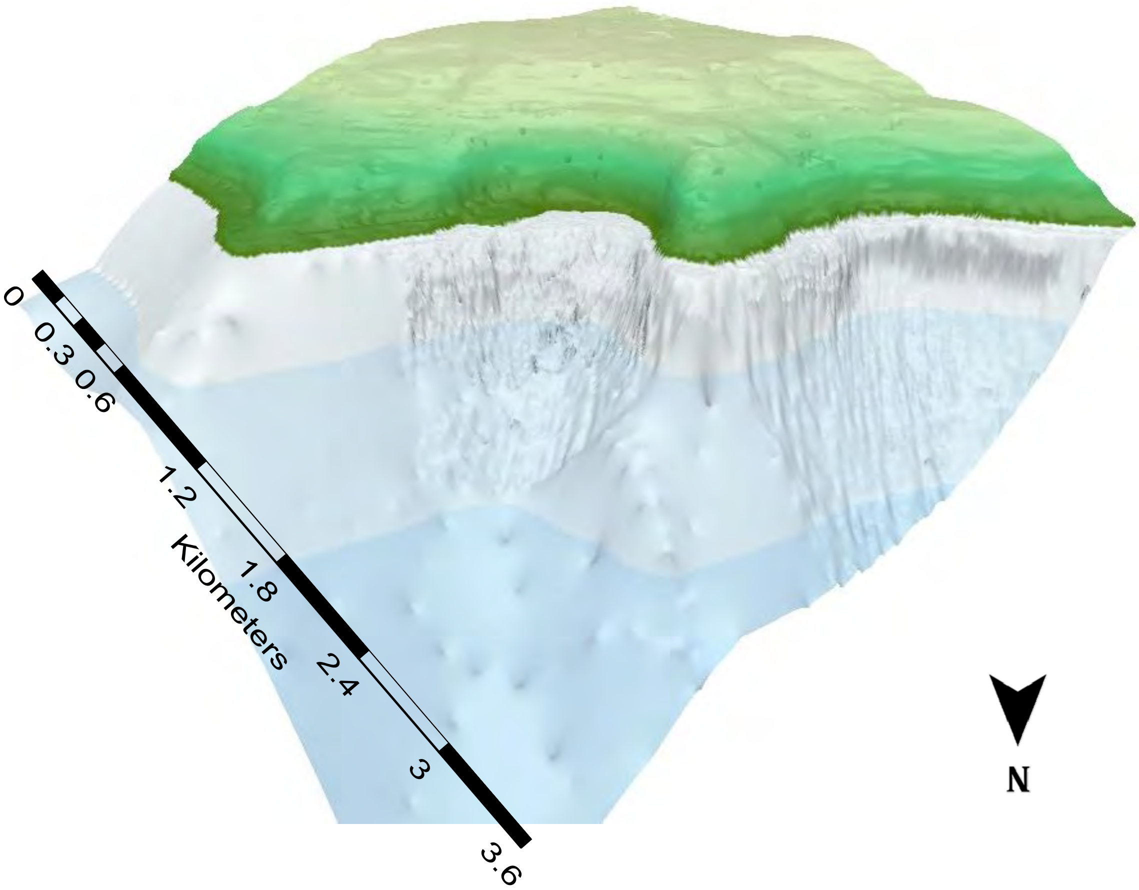

Figure 23: The Christmas Island Flying Fish Cove and Smith's Point 10 m grid (2 times vertical exaggeration).

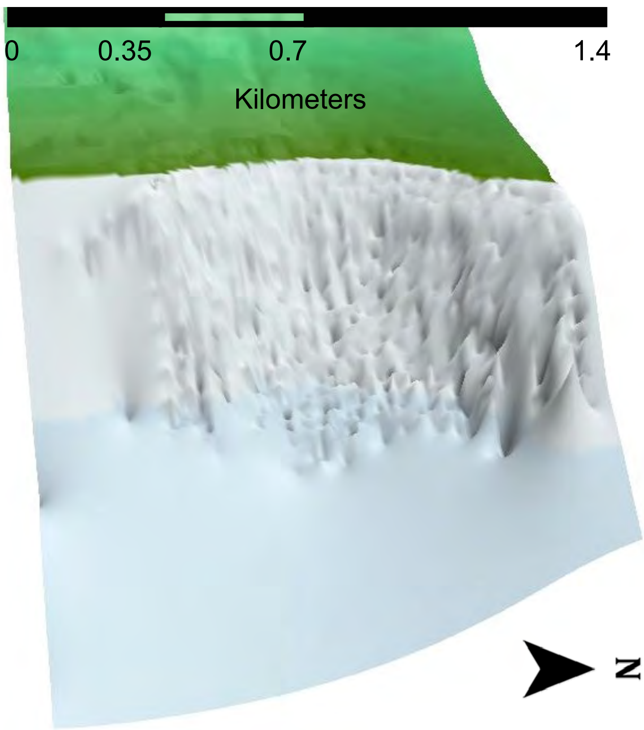

Figure 24: *The Christmas Island Norris Point 10 m grid (2 times vertical exaggeration).*

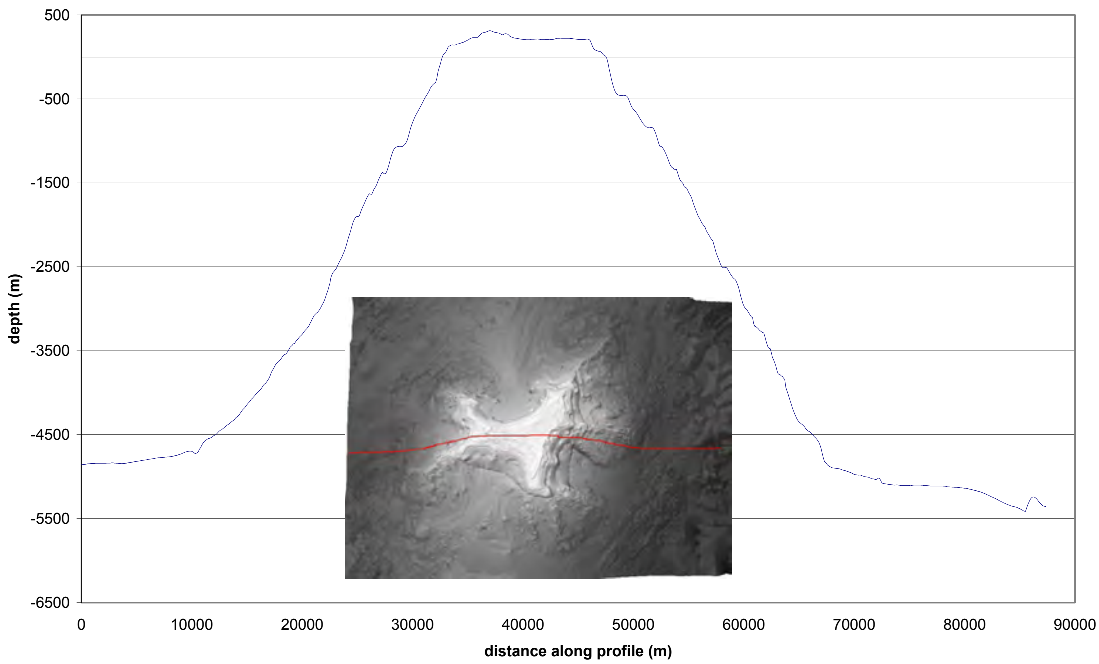

Figure 25: *The Christmas Island west-east profile (inset profile path in red).*

7. Final Grids

The Final Grids are known as:

1. FFC_10m_grid_2010 (.ers, .sd, .xyz …)
2. Norris_10m_grid_2010 (.ers, .sd, .xyz …)
3. Christmas_50m_grid_2010 (.ers, .sd, .xyz …)
4. Christmas_100m_grid_2010 (.ers, .sd, .xyz …)
5. Christmas_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 1 provides the ANZLIC compliant metadata.

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

- Show a high level of detail in the bay areas of Christmas Island.
- Show a good level of detail down the flanks of the seamount.
- Show the island in the correct spatial location and in its correct form.

These grids are made up of many different datasets 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

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 just 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 Christmas Island region. This prototype used all the data available at the time which included singlebeam, multibeam and chart data. The resulting grid for the Christmas 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

Further mapping should ideally be conducted with a high resolution system such as GA's EM3002 system, which is excellent to about 80 m 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 Christmas Island grid from this work.

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Appendix

ANZLIC METADATA RECORD

Metadata Element	Entry
ANZLIC Identifier	ANZCW0703013942
Title	High Resolution Bathymetry Grids of Christmas Island.
Custodian	Geoscience Australia
Jurisdiction	Australia
Abstract	Christmas Island is located approximately 2,600 North West of Perth. It is the surface expression of an emergent seamount uplifted by tectonics. 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. Six 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	105^{o} -10.0^{o}, 106.5^{o} -10.0^{o}, 106.5^{o} -11.0^{o}, 105^{o} -11.0^{o}
North Bounding Latitude	-10.0^{o}
South Bounding Latitude	-11.0^{o}
East Bounding Longitude	106.5^{o}
West Bounding Longitude	105^{o}
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. Three swath datasets acquired between 2004 and 2008 were used. Both surveys supply extensive regional coverage. Topography data of Christmas were obtained from the GEMD GIS. Eleven singlebeam surveys from the GA MARDAT database. These data range in vintage from 1959 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 in 2002 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. No attempts have been made to compare bathymetry from high quality datasets to that which would be obtained from lesser datasets, 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., 2010. The Creation of High Resolution Bathymetry Grids for Christmas Island. Geoscience Australia Record, 2010/37.