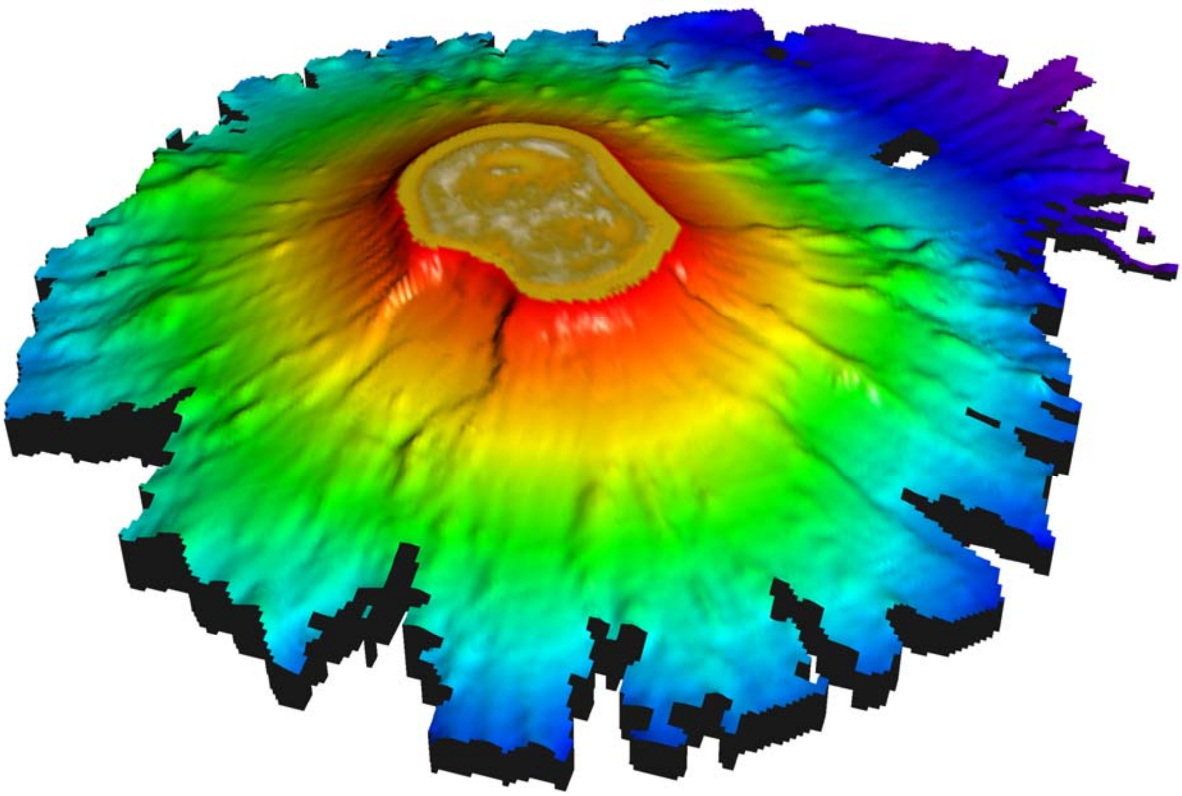
EU EDF 8/9 – SOPAC Project Report 116
Reducing Vulnerability of Pacific ACP States

NAURU TECHNICAL REPORT
High-Resolution Bathymetric Survey
Fieldwork undertaken on 30 September 2005

October 2008



Three-dimensional perspective digital terrain model of Nauru

Prepared by:
Jens Krüger and Ashishika Sharma
SOPAC Secretariat
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PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
c/o SOPAC Secretariat
Private Mail Bag
GPO, Suva
FIJI ISLANDS
http://www.sopac.org
Phone: +679 338 1377
Fax: +679 337 0040
www.sopac.org
director@sopac.org

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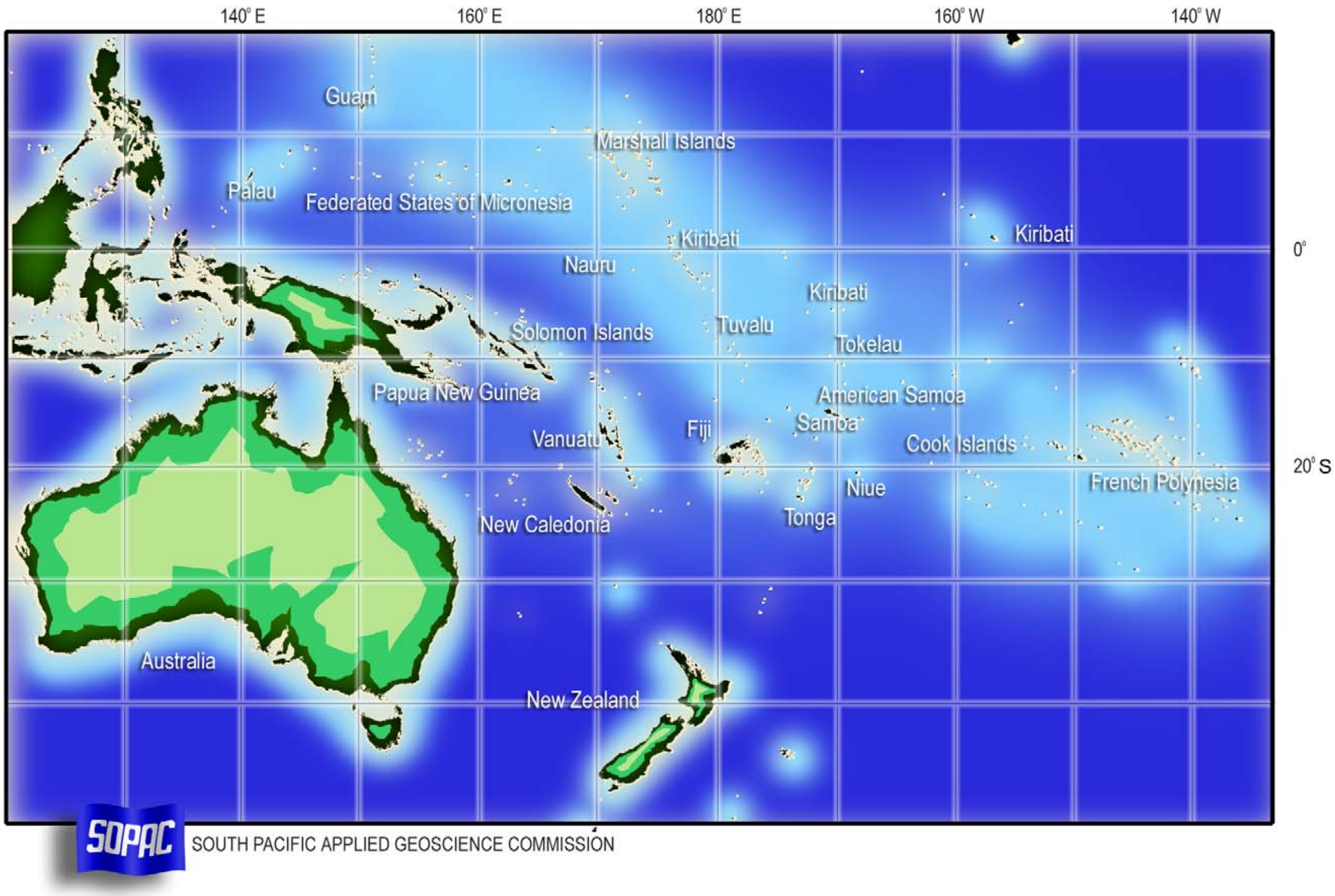


Figure 1. Location map of Pacific Island countries and territories constituting SOPAC.

Acronyms and their meaning	
ACP	African, Caribbean, and Pacific
ADV	Acoustic Doppler velocimeter
ARGO	Array for real-time geostrophic oceanography
ASCII	American standard code for information interchange
CD	Chart datum
CTD	Conductivity – temperature – depth
DTM	Digital terrain model
EEZ	Exclusive economic zone
EU	European Union
GDEM	Generalised digital environmental model
GEBCO	General bathymetry chart of the oceans
GPS	Global positioning system
LAT	Lowest astronomical tide
MBES	Multibeam echosounder
MRU	Motion reference unit
MSL	Mean sea level
NOAA	National Oceanic and Atmospheric Administration
PI-GOOS	Pacific Islands global ocean observing system
RTK	Real-time kinematic
S2004	Global bathymetry grid merging GEBCO and predicted depths from satellite altimeter measurements
SOPAC	Pacific Islands Applied Geoscience Commission
TAO	Tropical atmosphere ocean array
UTC	Universal time co-ordinated (Greenwich meridian time, GMT)
UTM	Universal transverse Mercator
WGS	World geodetic system

EXECUTIVE SUMMARY

Krüger, J. and Sharma, A. 2008. High-Resolution Bathymetric Survey of Nauru. *EU EDF 8/9 – SOPAC Project Report 116*. Pacific Islands Applied Geoscience Commission: Suva, Fiji, vi + 28 p. + 1 chart.

The Pacific Islands Applied Geoscience Commission, SOPAC, carried out a marine survey in the waters around Nauru. The objective was to investigate the seabed and provide information about the nearshore water depths around the island using a multibeam echosounder (MBES).

This report describes a high-resolution bathymetric mapping survey of the seabed surrounding the island of Nauru. The survey was carried out on 30 September 2005, resulting in the acquisition of over 81 km of high-resolution MBES data.

The survey achieved 100 % coverage of the seafloor from approximately 50 m depth in the nearshore area to an average offshore distance of 3 km, reaching water depths of some 1800 m.

A review of external sources of available bathymetry was also undertaken, and the survey data was supplemented with publicly available data for Nauru's EEZ. The resultant data compilation was used to produce a bathymetry chart of Nauru at 1 : 25 000. This new bathymetric map gives a descriptive picture of the ocean bottom terrain, vividly revealing the size, shape and distribution of underwater features. It can serve as the basic tool for scientific, engineering, marine geophysical and environmental studies, as well as marine and coastal resource management.

1. INTRODUCTION

1.1 Background

This report describes a high-resolution bathymetric mapping survey of the seabed surrounding Nauru (Figure 2). The survey was conducted using a mid-ocean depth Multibeam echosounder, and carried out in just one day in September 2005, resulting in the acquisition of over 81 km of Multibeam echosounder (MBES) data. This work was initiated by the Pacific Islands Applied Geoscience Commission (SOPAC) and European Union (EU) Reducing Vulnerability of Pacific ACP States Project.

In addition to the bathymetric maps presented in this report and their relevance to the SOPAC/EU project, it is envisaged that data from the survey will be used to support activities in fisheries, mineral exploration, coastal management, and geo-hazard studies.

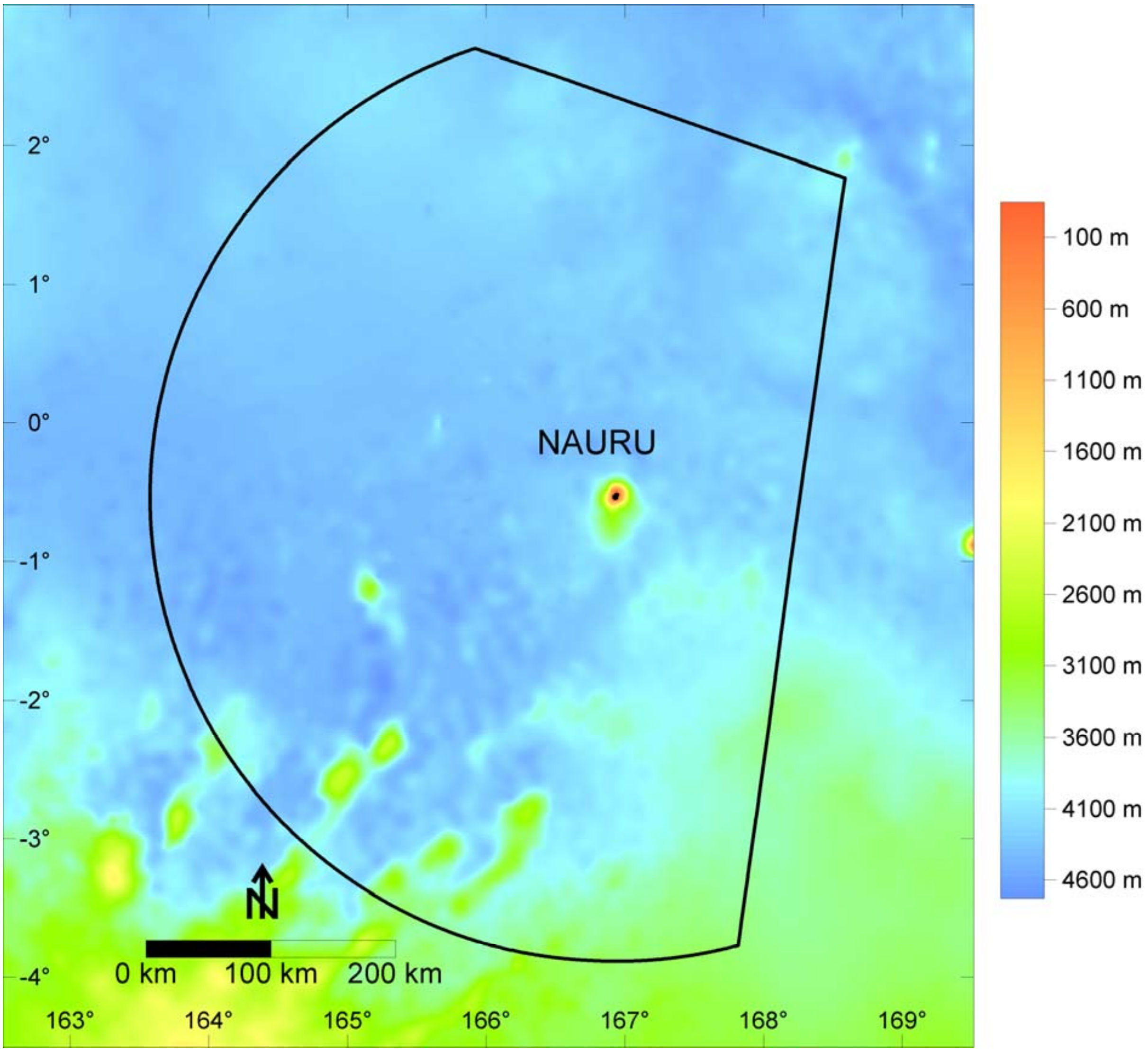


Figure 2. Bathymetric map of Nauru showing the island and approximate position of the exclusive economic zone. Bathymetric data are predicted water depths in metres (Smith and Sandwell 1997).

1.2 Geographic Situation

Geography of Nauru	
Location	Centred at 0°31'S and 166°56'E
Population	11 300 (1999 estimate from SOPAC country profile)
Land area	Total is about 21 km^2 with a maximum elevation of 70 m (location along plateau ring).
Coastline	Nauru rises from a sandy beach with a 19-km coastline encircling the island. There have been rapid changes in the coastal geography associated with increasing development. Coastal erosion is an increasing problem in Nauru due to the interruption of long-shore currents by development of boat channels, harbour facilities and the extension of the airport runway.
Tides	Semi-diurnal with a spring and neap range of 0.85 m and 0.24 m above MSL, respectively (Nautical chart NZ845).
Climate	Equatorial monsoon climate, with the rainy season from November to February. Mean temperature is 29 ºC and mean annual rainfall is 1500 mm.
Exclusive economic zone, EEZ	Approximately 320 000 km^2 in the central Pacific

1.3 Geological Setting

Nauru Island, located at 0°31'S and 166°56'E (Figure 1 and Figure 2), is a raised atoll comprising a single island with a maximum elevation of 71 m, approximately 6 km long (NE-SW) by 4 km wide (NW-SE). Figure 2 shows Nauru as an intra-plate island, some 4–5 km above the surrounding ocean floor of the southern Nauru Basin. The Nauru volcanic base was presumably constructed by hotspot volcanism during the mid-Eocene to Oligocene time, or 29 to 47 million years (Ma) (Jacobsen et al. 1997). It is estimated that the seamount is capped by about 500 m of limestone, with uplift and subaerial exposure of the carbonate platform during the Pleistocene, 1.6 Ma (Jacobsen et al. 1997).

1.4 Previous Bathymetry Compilations

Bathymetric maps are topographic maps of the sea floor, giving a descriptive picture of the ocean bottom terrain. With an EEZ of approximately 320 000 km^2, the available bathymetric data is limited, and the exact nature of the seafloor is poorly known. Most bathymetric data originates from sparse single-beam soundings from oceanographic cruises, and, since the early 1990s, from MBES systems as well as satellite-derived predicted depth. Apart from the SOPAC survey MBES 8160 data, the chart of Nauru has MBES data acquired by the NOAA ship RV *Ronald H. Brown* using a Seabeam 2121 multibeam system in 1999. It was not possible to source the original high-resolution MBES dataset, as the 1999 NOAA survey had an atmospheric focus, and the bathymetry was only a byproduct of this study. The data are available at a grid density of 111 m in the W-E direction and 11 m in the N-S direction. This is presumed to be the result of an accidental truncation of decimal geographic coordinates during transmission of the original dataset.

2. RESULTS

2.1 Bathymetry and Seabed Morphology

Bathymetric data provide information on the depth and morphology of the seafloor, as well as the shape and size of submarine features. Three bathymetry derivatives (slope angle maps, shaded relief maps, and three-dimensional rendered surfaces) were used in addition to the high-resolution bathymetry to aid visual interpretation of the seabed morphology. These derivatives are further defined in the table below.

Bathymetric Derivatives	
Slope angle	Slope is a measure of steepness between locations on the seabed, and is reported in degrees from zero (horizontal). Slope values are computed as a mean value for one grid cell from the slope gradient between it and the eight neighbouring grid cells.
Shaded relief	Shaded relief maps use shades of grey to indicate the local orientation of the seafloor relative to a user-defined light source direction. The light source can be thought of as the sun shining on a topographic surface, much like artificial hillshading that illuminates bathymetric roughness. Portions of the surface that face away from the light source reflect less light toward the viewer, and thus appear darker.
Three-dimensional surface	For three-dimensional surfaces the height of the surface corresponds to the depth of the seafloor.

The surveyed area extends from approximately 1 km offshore to the south and west, to a maximum of approximately 4 km to the east (see coverage map in Appendix 3. The bathymetry for this area is shown on Chart 1 contoured at intervals of 20 m. The chart also includes depth data collected by NOAA (RV *Ronald H. Brown*, Nauru99 campaign, SeaBeam system) contoured at 50 m isobaths, and smaller scale insets of 3D bathymetric images. A larger-scale bathymetric map showing details of the southwest coast of Nauru is shown in Figure 3.

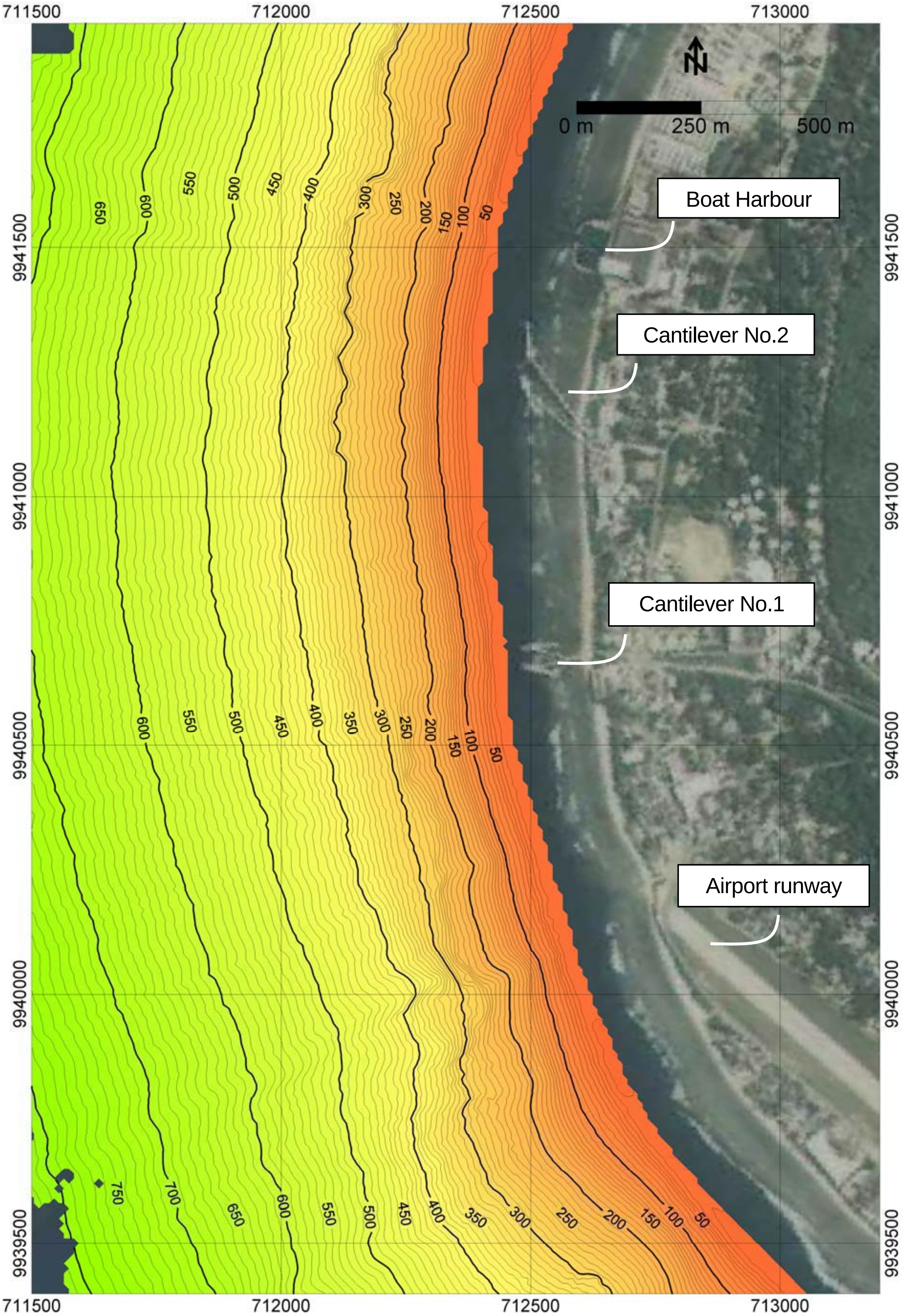


Figure 3. Bathymetric map showing details of the coastal infrastructure southwest of Nauru. Isobaths are contoured at 10 m intervals. The backdrop image is a rectified 1998 airphoto.

The water depth within the SOPAC/EU survey area around Nauru ranges from 3 to 1735 m. Within the 500 m isobath, or to a distance of approximately 800 m offshore, the submarine slope descends at about 45° (Figure 4 and Figure 5). Beyond this, the seabed deepens to the maximum at an average gradient of 31° near the seaward limits of the survey area. Locally, the seabed is expected to be quite irregular with gradients expected to be highly variable, ranging from 0 to 80º.

A near continuous scarp encircles the island in close proximity (350 m) to the coastline, with a depth to the headscarp of approximately 120 m, and a headscarp height of 60 m (Figure 6). This is believed to be a plateau rim attributed to subaerial exposure during subsequent sealevel lowstands, rather than an erosional feature caused by mass wasting. Further downslope, a second set of scarps, also subparallel to the coastline, occur in water depths of approximately 300 m. These are concentrated to the south and northeast of the island with a scarp height of approximately 80 m, and are associated with numerous channels that are orientated radially downslope of these deeper scarps.

The dominant seabed feature is the Anabar Bay submarine landslide located on the eastern flank of the Nauru edifice (Figure 6). The upslope arcuate scarp of this mass failure occurs in a water depth of 250 m and extends over a distance of approximately 4 km, with a maximum headscarp height of 400 m (Figure 4). The side walls of the Anabar Bay submarine landslide are near vertical, exhibiting maximum slope angles at 80° (Figure 5). The submarine landslide has significantly altered the subaerial shape of the island. The upslope region of the submarine failure is the arcuate eastern coastline of Nauru, facing Anabar Bay. This seaward convex bay and associated mass failure is believed to be a result of the highly fractured nature of island (Figure 7).

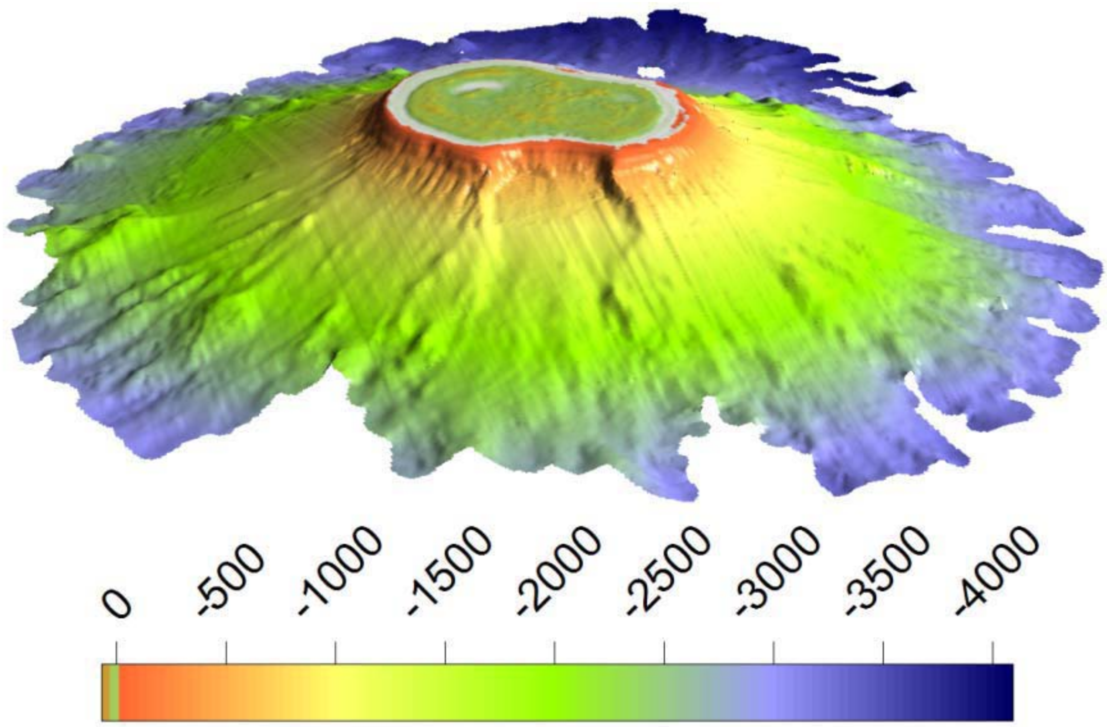


Figure 4. Three-dimensional perspective image of the Nauru digital terrain model (DTM) looking west. There is no vertical exaggeration, but scale varies with distance in this perspective view. The DTM is a composite of (i) land topography provided by the Space Shuttle Radar mission, SRTM; (ii) SOPAC/EU MBES bathymetry data from approximately 50 to 1800 m; (iii) NOAA MBES bathymetry data. See text for further details on data sources.

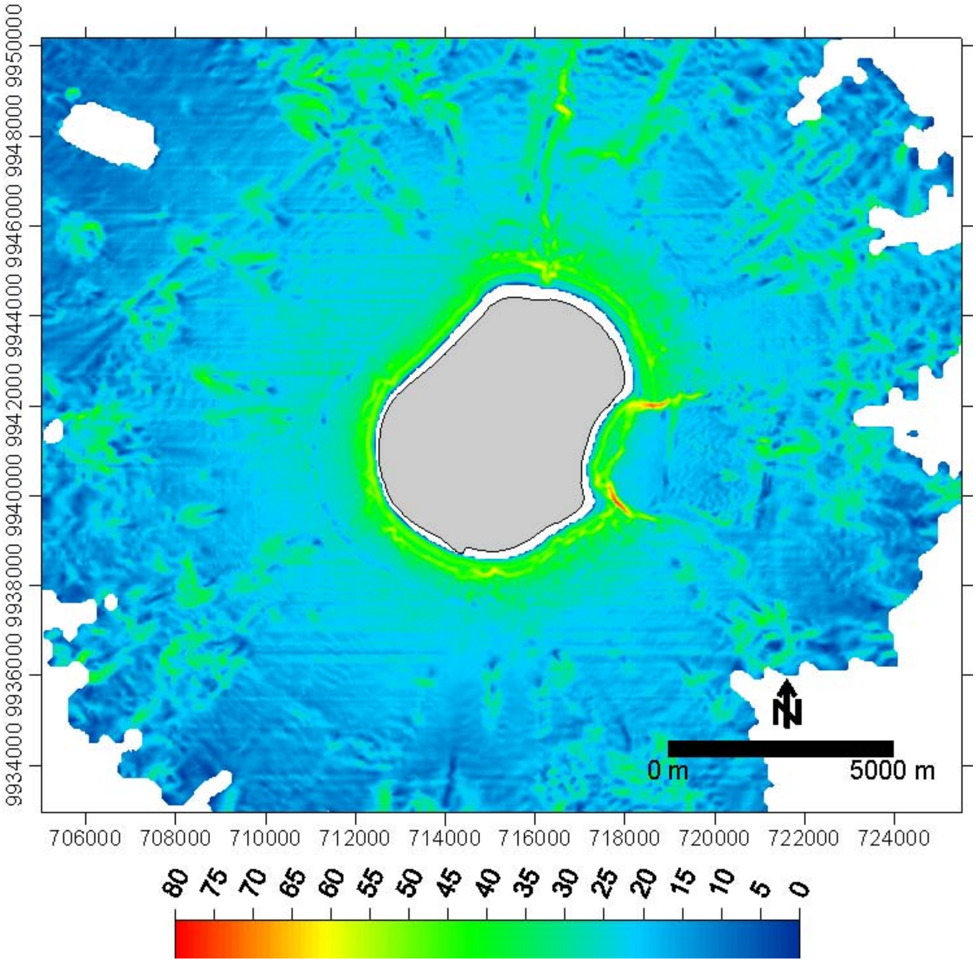


Figure 5. Gradient slope angle map of the Nauru seabed generated from 50 m gridded bathymetry. Red indicates higher slope angles, and blue indicates near-horizontal seafloor.

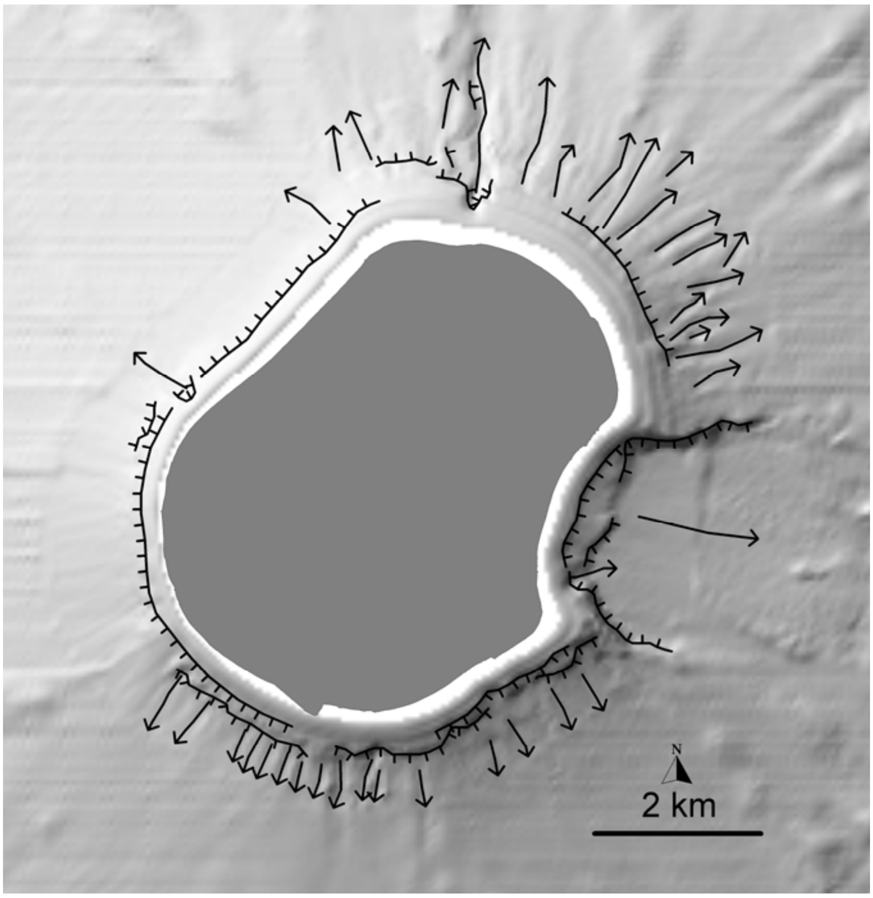


Figure 6. Shaded relief image of Nauru bathymetry illuminated from the NW. Major canyons and channels are shown as arrows indicating downslope sediment pathways. Slopes with angles ≥ 60° are shown as lines with hatch marks pointing downslope. The dominant feature of the Anabar Bay submarine landslide can be seen along the eastern shoreline.

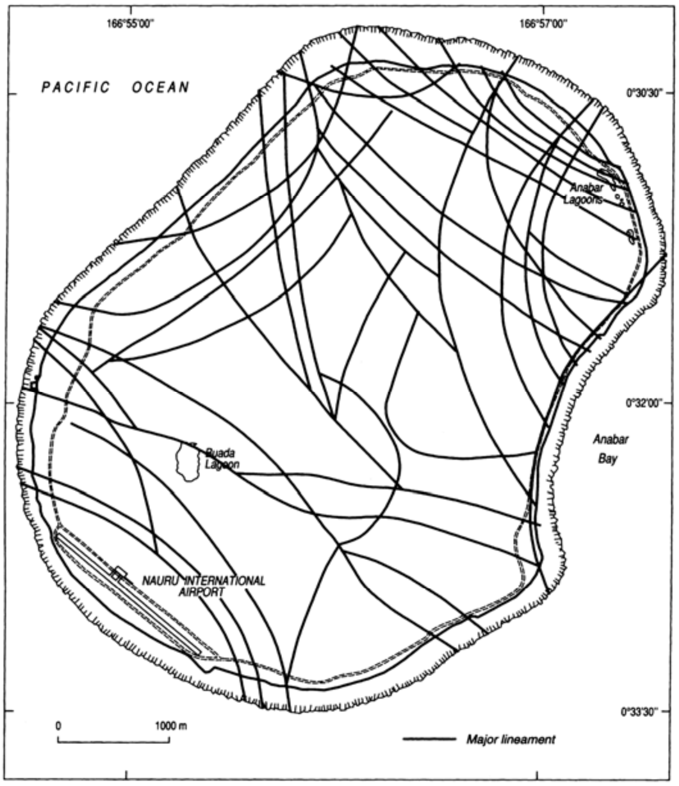


Figure 7. Major lineaments from photo interpretation (from Jacobsen et al. 1997, after Barrett 1988).

3. DATA ACQUISITION AND PROCESSING

3.1 Fieldwork Summary

Survey Particulars	
Survey vessel	MV *Summer Spirit*
Fieldwork date	30/09/2005
Equipment used	Reson 8160, deep water MBES

All dates and times in this report are given in the local Nauru time zone (12:00h GMT = 24:00h local).

3.2 Field Personnel

SOPAC	
Jens Kruger	Chief Scientist
Peni Musunamasi	Electronics Engineer

Vessel	
Brian Hennings	Master
Gordon Elliot	Officer
Nelson Tafilangi	Engineer
Ram Reddy	Cook

3.3 Geodetic Reference System

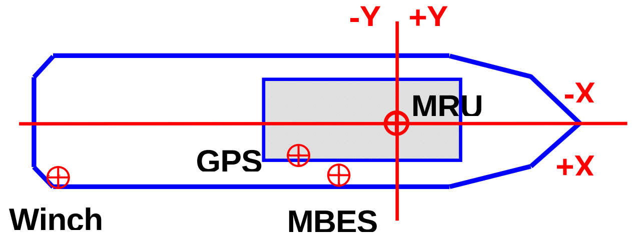
The survey results were mapped in terms of the following geodetic reference system:

Geodetic datum	WGS84	
Ellipsoid	WGS84	
	Semi-major axis (a)	6378137.000
	Semi-major axis (b)	
	Inverse flattening (1/f)	298.257223563
	Eccentricity sq. (e2)	
Projection	Utm zone 58 south	
	Projection type	Transverse Mercator
	Origin latitude	00° 00' 00.000" North
	Origin longitude	165° 00' 00.000" East
	Origin false easting	500000.0000
	Origin false northing	10000000.0000
	Scale factor	0.9996000000
	Grid unit	metres
Geodetic transformation	From WGS84 (GPS satellite datum) to UTM 58 South	
	Source coordinate system	WGS84
	Target coordinate system	UTM 58 South
	Transformation parameters	
	dX	0.00
	dY	0.00
	dZ	0.00
	rX	0.00000
	rY	0.00000
	rZ	0.00000
	Scale	0.00000

3.4 Vessel Description and Static Offsets

Sensor	X (m)	Y (m)	Z (m)
Reference point at water level	0.00	0.00	0.00
Motion Reference Unit (MRU)	0.00	0.00	1.82
Positioning Antenna (GPS)	1.92	–6.92	–6.29
Multibeam Echo Sounder (MBES)	0.86	–3.96	0.80
Winch	–14.29	1.92	–3.00

Vessel	
Name	*Summer Spirit*
Length overall	25 m
Breadth (mid)	6 m
Draft (mid)	2.5 m
Displacement	65 t
Port of registry	Brisbane
Registration No.	IQ115Q
Call Sign	3DTF
Vessel Type	Mono-hull motor yacht (Fig. 8)



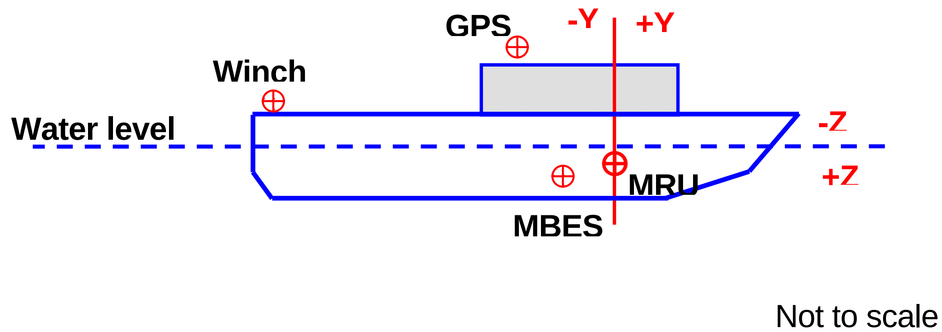


Figure 8. The chartered survey vessel RV *Summer Spirit*.

3.5 Positioning Control

The vessel's reference point (X=0, Y=0, Z=0) was the motion reference unit (MRU) position at the waterline. Positioning was by stand-alone GPS, using an Ashtech Aquarius dual-frequency P-code receiver. A good satellite constellation status was observed throughout the survey. The patch test was conducted in Suva, Fiji, using RTK GPS.

3.6 Survey Computer

The survey computer was a Windows 2000 PC running Hypack 4.3. This computer was used for continuous on-line data logging and computation of positioning and digital bathymetry. The package also provided a line control display for the helm. The on-line operator continuously monitored a range of quality control parameters.

An off-line Hypack 4.3A package was used in the office for replaying and post-processing of track data and bathymetry. An A0 plotter was available for the production of charts.

3.7 Multibeam Echosounder

A Reson SeaBat 8160 multibeam echosounder (MBES) was temporarily installed on MV *Summer Spirit*, and used to provide swathe bathymetry data. An MBES provides high-resolution information about the depth of water from the surface to the seafloor in a water body. The main instrumental and operating parameters are listed below.

Instrumentation	
Multibeam echosounder	Reson SeaBat 8160
Transducer mount	Starboard hull-mounted
Motion reference unit	TSS DMS 2-05 Dynamic Motion Sensor
Gyro	SG Brown Meridian Surveyor Gyro Compass
Sound velocity probe at transducer	Installed

Operating Parameters	
Transducer Frequency	50 kHz
General water depth	10–2500 m
Average ship's speed	7 knots (3.6 m/s)
Transmit Power	Variable 1–16
Pulse length	Variable 0.5–10.0 ms
Horizontal coverage	Approximately two times water depth
No of beams / beam spacing	126 / 1.5 °
Ping rate	Variable, maximum of 4 Hz

Dynamic Offset Calibration	Suva, Fiji, 30/08/2005
Roll correction	–0.50
Pitch correction	0.00
Yaw correction	–1.00
GPS Latency correction	0.80
Gyro correction	Not determined

The dynamic calibration offsets for the MBES were determined during a pre-survey patch test conducted in Suva, Fiji, using DGPS. The patch test and bar check were performed in accordance with procedures contained in USACE (2002).

3.8 Multibeam Echosounder Data Processing

Upon return to the SOPAC office in Suva, Hypack 4.3A software was used for the post-processing of the MBES survey data. Post-processing is a form of data reduction, which involves checking, calibration, cleaning and preparation necessary to convert raw measurements into a form suitable for analysis, application and presentation. The product of post-processing is in the form of ASCII listings of gridded easting, northing, and depth (XYZ) points. Gridded XYZ points from Hypack were used in Surfer 8.05 to produce final charts and figures. The processing and chart production sequences are listed below.

Post-processing Sequence	
Phase 1	Correct for heading, heave, roll, pitch, navigation errors. Apply tidal and sound velocity corrections.
Phase 2	Filter to remove poor-quality beams and spikes. Manual editing to remove outliers from individual survey lines.
Phase 3	Apply 2nd standard deviation filter to remove outliers from median depth from overlapping coverage. Final manual editing to remove outliers.

Post-processing Sequence	
XYZ output	ASCII XYZ files (easting, northing, depth) are in the project coordinate system. The final output typically consist of a file that includes all post-processed sounding points, as well as files of reduced points at grid dimensions of 20, 50, and 100 m.

Chart Production Sequence	
XYZ to grid	XYZ data are reduced and gridded to 1 mm (0.1%) at the charting scale (e.g. 50 m grid size for a chart scale of 1 : 50 000).
Digital terrain model (DTM)	A surface model is created from the grid. A search radius of approximately three times the grid spacing is used to fill data gaps. The DTM is also blanked against regions that contain no valid data such as land and reef areas.
Chart output	Various levels of smoothing are applied to the DTM and contours to give a realistic impression of the seabed, without removing any real features from the data set.

3.9 Tidal Information

Soundings were reduced to the Nauru Island Datum defined as 0.229 m below LAT, 1.3986 m below mean sea level (MSL 1993–1994), and 7.2930 m below the fixed height of Benchmark NAU 1 (see Figure 9), using observed water levels from the Nauru tide gauge provided by the Australian Bureau of Meteorology (http://www.bom.gov.au/oceanography/) through the South Pacific Sea Level and Climate Monitoring Project (http://www.pacificsealevel.org/).

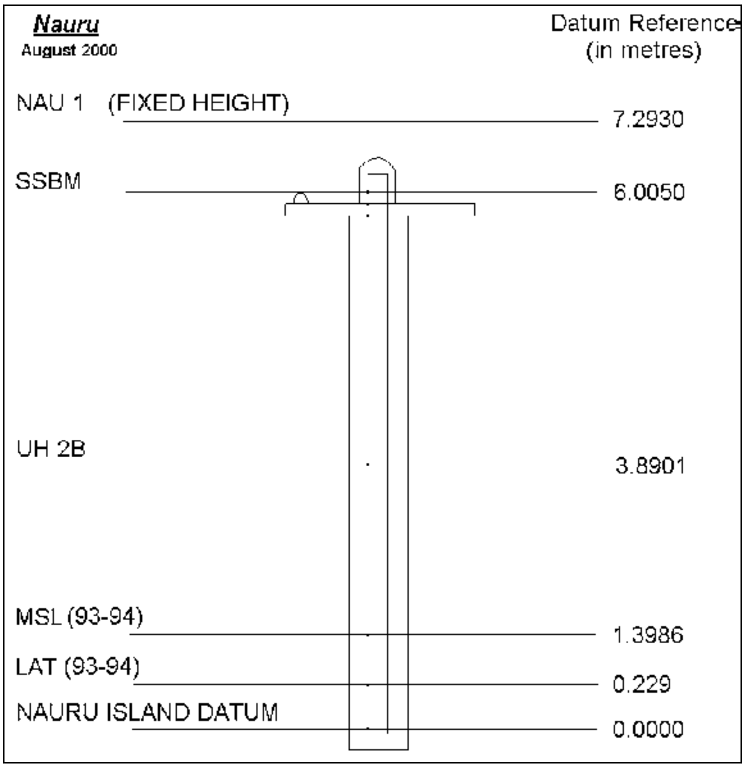


Figure 9. SEAFRAME tide gauge datum definition and other geodetic levels at Nauru (from NTFA 2002).

3.10 Sound Velocity Profiling

The accuracy of the depth soundings depends in part on the variation of the speed of sound with water depth. This is because the path of a ping of sound energy emitted from the echosounder into the water is usually not straight. Therefore, the speed-of-sound profiles are required to correct for the refraction path travel times, and to find the correct depth and location of soundings. The speed of sound in seawater varies with temperature, salinity and depth, and was determined by measuring the conductivity, temperature and depth (CTD) through the water column. The main instrumental, operational, processing parameters are listed below.

CTD Instrumentation	
Make	SeaBird Electronics
Model	SeaCat 19+ (self-powered, self-contained)
Serial number	4172
Depth rating	3000 m

Operating Parameters	
Sample rate	1 scan every 0.5 s
Maximum depth	Limited to 400 m due to wire rope length
Data recorded	Profiles of conductivity, temperature, and pressure

Data Processing	
Positioning	The profile position was taken at the GPS antenna near the start of the downcast. No allowance was made for instrument or vessel drift over the duration of the profile, which may be significant (>500 m).
Data conversion	Convert raw data (.hex) to a .cnv file. The following values are output from the recorded data: Pressure, dbar Depth, m (derived using salt water at local latitude) Temperature, °C (ITS-90) Salinity, psu (derived) Density, kg m^{-3} (derived) Sound velocity, m/s (derived using Chen and Millero, 1977)
Bin average	Average data into 1 m depth bins. No filtering was applied.
Output	Processed data is saved in ASCII text format with the file name date_location_bin.cnv.

The CTD profile details are listed below. The summary of the CTD profile data in graphical form is shown in Appendix 3.

Profile location	Date	Time	Easting	Northing	Depth (m)
Nauru	30/09/2005	15:59	718892.44	9940445.73	960

The on-board CTD probe could only be operated to a maximum depth of 400 m, due to restrictions on the wire rope length. In order to ensure corrections to a maximum sounded depth of approximately 1800 m below sea level, the ship-based profile data were complemented with data from an ARGO float and the GDEM model. Figure 10 shows the locations of these external sources, and their parameters are given below.

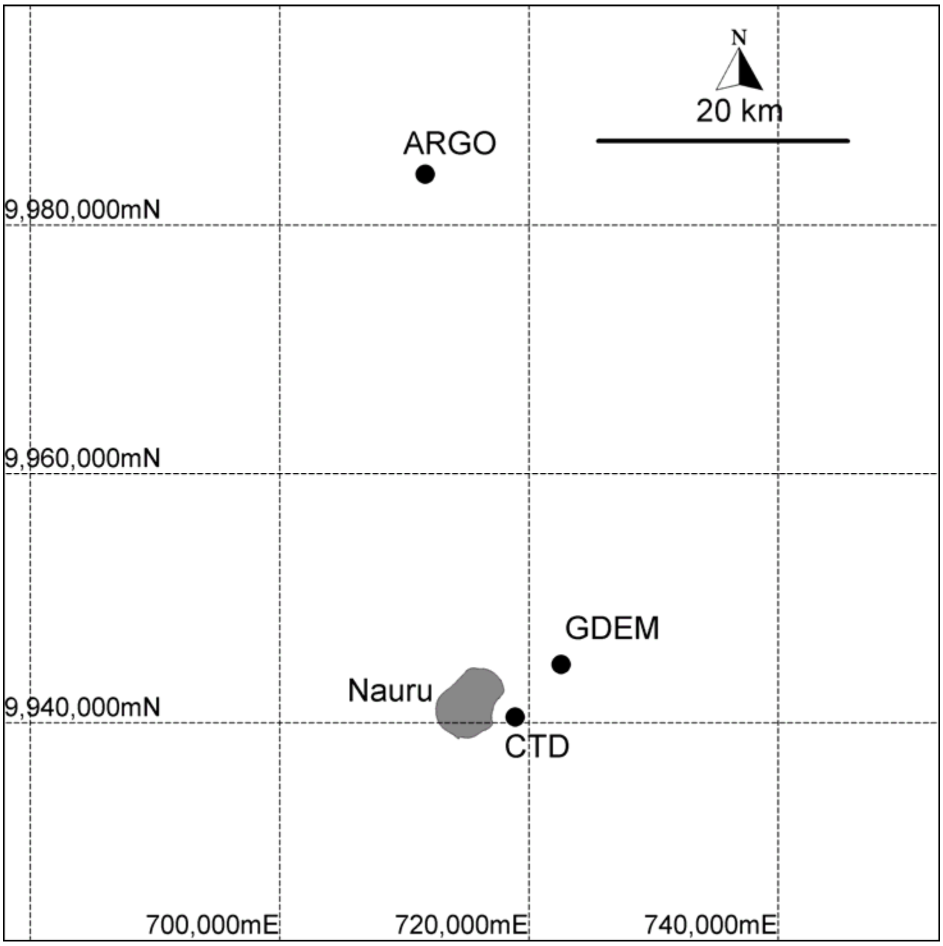


Figure 10. Map showing the location of CTD, ARGO and GDEM profiles.

Array for real-time geostrophic oceanography (ARGO) float	
Profile ID	R5900910_017
Date	30/09/2005
Latitude	0.144 ºS
Longitude	166.902 ºE
Easting	711683
Northing	9984074
Available data	Pressure, salinity, temperature
Bin size	From 6 to 60 m, increasing with depth
Maximum depth	1513 m

Generalised Digital Environmental Model Data (GDEM)	
Data file version	3.0, URL accessed on 3/04/2006
Date	Monthly average for September
Latitude	0.5 ºS
Longitude	167 ºE
Easting	722587
Northing	9944701
Available data	Depth, temperature, salinity, sound velocity
Bin size	From 10 to 100 m, increasing with depth
Maximum depth	3800 m

The Argo temperature-salinity profiles were used to calculate the speed of sound utilising the Chen-Millero equation (Chen and Millero 1977). The Argo data were collected and made freely available by the International Argo Project and the national programmes that contribute to it (www.argo.ucsd.edu, argo.jcommops.org). Argo is a pilot programme of the Pacific Islands Global Ocean Observing System (PI-GOOS). The GDEM model provided a monthly mean of sound velocity based on a 2.5º grid.

The final sound velocity profiles used to correct MBES data were therefore a construction from three sources according to depth, as shown in the table below, and illustrated in Figure 11.

Sound Velocity Data Source	Water Depth
CTD casts	0 to 358 m
Argo floats	363 to 1513 m
GDEM model	1600 to 2000 m

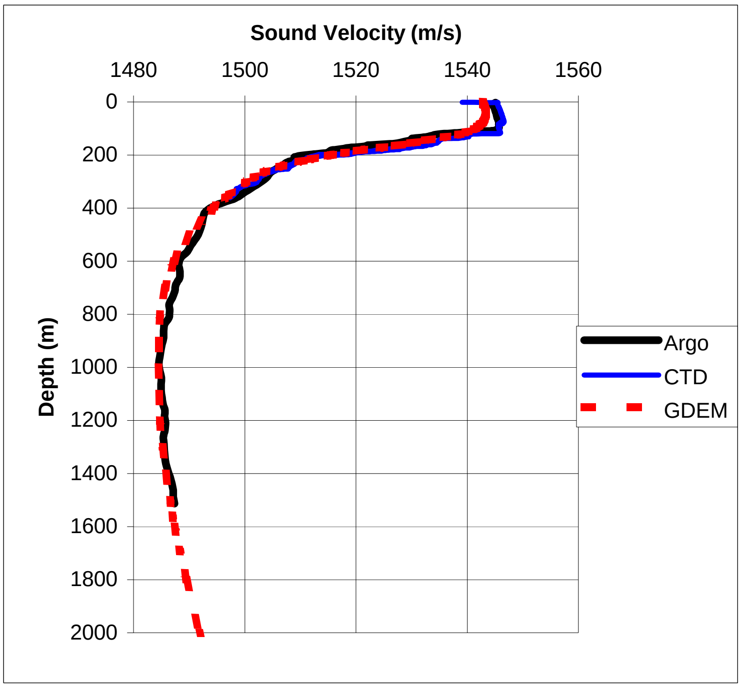


Figure 11. Plot showing the sound velocity profiles used for MBES data correction (see Figure 10 for location). The fine blue line in the upper water column is the data derived from the CTD cast. The solid black line extending to 1513 m is derived Argo data, and the dashed red line to a depth of 2000 m is the GDEM data.

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APPENDICES

Appendix 1 – Statement of Accuracy and Suitability for Charting

Bathymetric maps are topographic maps of the sea floor. The bathymetric map serves as a basic tool for performing scientific, engineering, marine geophysical and environmental studies. The information presented in this report and enclosed charts are intended to assist persons and authorities engaged in recreation, tourism, marine resource related industries, hydrographic mapping, coastal development, trade and commerce, sovereignty and security, and environmental management. It is consequently important that users be informed of the uncertainties associated with the data and with products constructed from it. The following is an outline of the survey equipment used and the operating principles, including limitations and estimates regarding the data accuracy.

A1.1 Horizontal positioning

The methods used to acquire survey data will affect the final product accuracy. The global positioning system, GPS, uses radio signals from satellites that orbit the earth to calculate the position of the GPS receiver. Stand alone GPS has an estimated accuracy as good as approximately 10 m, depending on satellite configuration and atmospheric conditions. In addition to this, equipment and measurement errors also need to be considered.

A general rule of thumb is that surveys should be conducted with a positioning accuracy of 1 mm at the scale of the chart. Therefore, at a chart scale of 1 : 10 000, the survey would be required to be accurate to 10 m.

The present S-44 4th Edition Standard of the International Hydrographic Office (IHO) includes a depth-dependent factor that takes into account the added uncertainty of the positions of soundings from multibeam echo sounder (MBES) systems as water depth increases. The relevant survey orders are listed below, with multibeam surveys conducted by SOPAC generally falling into orders 2 or 3.

Survey order	Application	Recommended horizontal accuracy
Order 1	Harbours and navigation channels	5 m + 5% of depth
Order 2	Depths < 200 m	20 m + 5% of depth
Order 3	Depths > 200 m	150 m + 5% of depth

For the purpose of this survey, it was assumed that the use of stand-alone GPS provided adequate precision in terms of horizontal position. Therefore, it is not recommended to interpret nearshore data at scales larger than 1 : 10 000, or a grid size smaller than 10 m. For areas with water depths greater than 200 m, a charting scale of at least 1 : 50 000 is recommended.

A1.2 Depth measurements

Bathymetric maps provide information about the depth of water from the water surface to the seabed. Through the use of detailed depth contours and full use of bathymetric data, the size, shape and distribution of underwater features are clearly revealed. The depth is measured using a ship-mounted multibeam echo sounder. The MBES transducer produces an acoustic pulse designed as a fan that is wide in the across-track and narrow in the along-track direction (Figure A1.1). The swath of seabed covered by this transmit beam is typically more than twice the water depth. The pulse of sound emitted from the MBES travels through the water column and is reflected back as an echo and received as numerous narrow beams by the receiving elements of the MBES. The measurements are time based, and by using the speed of sound in seawater each time is converted first to a range and then, knowing the beam angle, to a depth. The distance to the seabed is then combined with the movement of the vessel to stabilise it into a real-world framework. This framework is then positioned to provide XYZ soundings for each beam's interaction with the seabed. A series of these swaths are then combined to produce a three-dimensional representation of the seafloor topography.

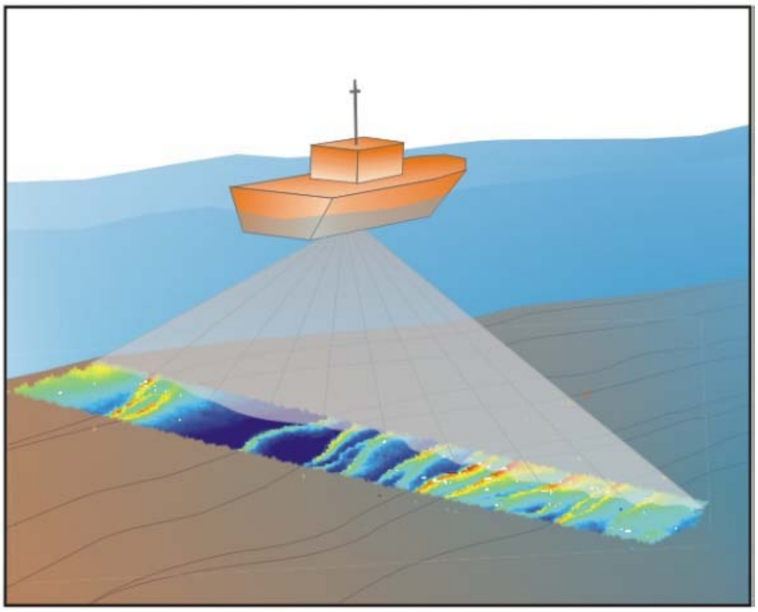


Figure A1.1. Conceptual illustration of bathymetric data acquisition with a multibeam echosounder, MBES (source: http://www.rcom.marum.de, accessed 10/01/2007).

The accuracy of the MBES system is critically dependent on the corrections applied for vessel motion (heave, pitch, roll, yaw, and heading). However, the absolute accuracy of single beam and multibeam bathymetry depends on several factors that are not easy to determine. For single-beam data, probably the principal errors that may be introduced are due to topographic features falling between survey lines. Multibeam systems give far better coverage.

The S-44 4th Edition Standard of the IHO lists values "a" and "b", which should be introduced into the following equation to calculate the error limits for depth accuracy:

$\pm\sqrt{a^2 + (b \times d)^2}$, where d = depth.

Survey order	Application	Constants
Order 1	Harbours and navigation channels	a = 0.5 m, b = 0.013
Order 2	Depths < 200 m	a = 1.0 m, b = 0.023
Order 3	Depths > 200 m	a = 1.0 m, b = 0.023

For example, the IHO recommends that a near-shore coastal survey (Order 2) in water depths of 20 m should have a maximum depth error of ± 1.1 m.

A MBES has, as any other measuring instrument, an inherent limit in its achievable accuracy. The total measurement accuracy, i.e. the uncertainty in the depth and location of the soundings, also depends upon the errors of the auxiliary instruments such as the motion reference unit, the gyro compass, and the measurements of the speed of sound through the water column. The sea state at the time of the survey also contributes significantly to the quality of the data. The possible accuracy of the measured depths may be estimated by considering the following main error sources.

Error budget analysis for measured depths	
Measurement	The nadir-beam bottom detection range resolution of the multibeam system has a maximum limit of 0.1 m (Reson, 2002). However, multibeam systems are particularly susceptible to errors in the far range (outer beams), and detection is estimated at ± 0.3 m plus 0.5 % of the depth. Errors also include the detection of the sea floor due to local variations of depth within the beam footprint, especially in the outer beams, and a varying density of the bottom material. This may be significant if a relatively low-frequency transducer is used on soft marine muds in shallow water.
Transducer draft	The transducer depth below the water line may be determined to ± 0.1 m. However, the draft of the vessel due to the variability in vessel loading, e.g. fuel and fresh water storage, was not determined. It is estimated that this introduced a water depth-independent error of up to ± 0.2 m. Dynamic draft errors, e.g. vessel squat, may also be significant.
Sound velocity	The sound velocity profiles measured by the conductivity-temperature-depth sensor (CTD) probe did not reach full survey depths in waters exceeding 400 m water depths. An inaccurate sound path from the transducer to the bottom and back will affect not only the observed depth of water, but also the apparent position of the observed sounding. This error is presumed to exceed 0.5% of the water depth beyond the direct CTD measurements. In order to minimise this error, ARGO and GDEM data may be used to supplement the CTD data.
Heave	This error is directly dependent on the sea state, the sensitivity of the motion sensor and installation parameters. The MRU installation did not account for the offset distance between MRU, the centre of gravity, and the MBES transducer mount. However, the software was able to perform lever arm calculations and heave compensation during post-processing, and the vertical error is assumed to be significant only in heavy seas.
Tide/water level	Errors due to tides may be significant, especially where predicted tides some distance from the survey area are used. Perhaps ± 0.3 m for uncertainty in tidal datum need to be considered.

From the table above, it is estimated that the measured depths in 20 m are typically accurate to about ± 1.1 m (± 0.3 m root mean square). However, the complete bathymetric model, or digital terrain model (DTM), is based on some form of interpolation between the sampled depths from several survey lines. Consequently, the total uncertainty associated with a bathymetric model will include uncertainties due to horizontal positioning, and uncertainties introduced by the interpolation process, and will therefore be larger than the depth sounding uncertainty.

A1.3 Multibeam Echosounder Data Density

The density of data used to construct a bathymetric grid is an important factor in its resolution – the denser the data, the higher the resolution that can be achieved. Sounding density is critical in terms of seabed feature detection and delineation. The two main factors that control the potential bathymetric target resolution capability of a multibeam echosounder are the distance between individual soundings (both in the cross-track and along-track dimensions), and the footprint size. The footprint is the area on the seabed covered by the sound pulse. Footprint size is a function of range, beam angle, and receiver and transmitter beam widths. A high sounding density and small footprint will result in higher-resolution data. Conversely, the target detection capability is going to decay as a result of a growing projected beam footprint and decreasing data density.

The along-track spacing is controlled by the ping rate, which in turn is limited by the two-way travel time from the source to the seafloor. The maximum across-track spacing depends again primarily on the range, but also on the equiangular beam spacing. The size of the beams received by the MBES system is between one and one-and-a-half degrees. This means that a system mounted on a ship will have an increasing projected footprint size with increasing water depth. The footprint will also be larger at the outer beams than at the centre of the swath, as the range and incident angles increase with distance from the nadir beam. It is possible to have local variations of depth within the beam footprint, causing vertical error and affecting amplitude detection.

The table below shows a summary of the projected beam footprint size under varying water depths for the two MBES systems currently in use by SOPAC. It should be noted that the higher-frequency system (SeaBat 8101) is not appropriate for applications in waters deeper than 200 m. Due to the constant beam width; the sounded area varies according to the depth and slope, which results in a variable data density in the survey area.

Water depth	SeaBat 8160 (deep water) 50 kHz, 126 beams at 1.5 °		SeaBat 8101 (shallow water) 240 kHz, 101 beams at 1.5 °	
(m)	Inner footprint at nadir (m)	Outer footprint at 65º (m)	Inner footprint, nadir (m)	Outer footprint (m)
20	0.5	2.8	0.5	3.5
50	1.3	7.0	1.3	17.6
100	2.7	14.0	2.6	35.3
200	5.3	28.0	5.2	70.6
500	13.3	69.9	N/A	N/A
1000	26.7	139.8	N/A	N/A
1500	40.0	209.8	N/A	N/A
2000	53.4	279.7	N/A	N/A

The table above assumes a horizontal seabed, and shows the variation in across-track footprint size with water depth and beam angle. The sounding density and swath width will also vary when surveying steep slopes, or highly incised margins, as the footprint size varies strongly with topography. Therefore, deeper sections have larger projected footprints and fewer data point. This has the effect that a bathymetric feature whose lateral dimensions are less than the beam footprint size will not be resolved.

It should also be noted that the along-track resolution usually exceeds the across-track resolution due to ping rates, especially in deep water, since ping rates are limited by the two-way travel time. Rates for water depths of 20 m and 1500 m are 12.9 and 0.2 pings per second, respectively. Using maximum ping rates, or when surveying in deep water, the same area may be measured with the outer beams for several pings, which may give inconsistent sounding data due to the poor repeatability on uneven seabed. In order to take into account depth-dependent point density, it is generally accepted to grid bathymetric data at a resolution that is of the order of the average beam footprint size, typically 10% of the water depth.

Appendix 2 – Multibeam Echosounder Coverage

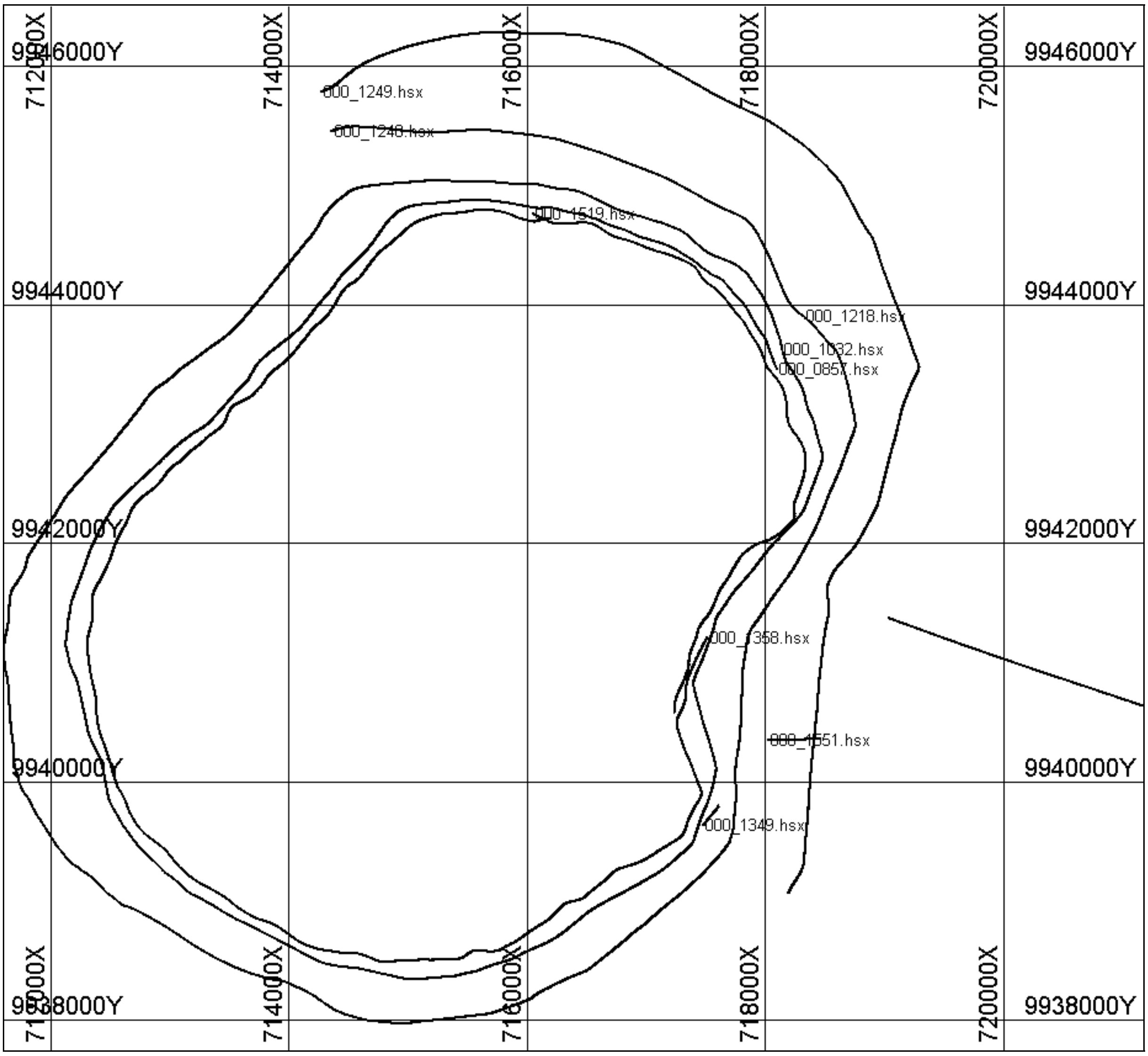


Figure A2.1. Map showing the SOPAC/EU MBES survey lines for Nauru.

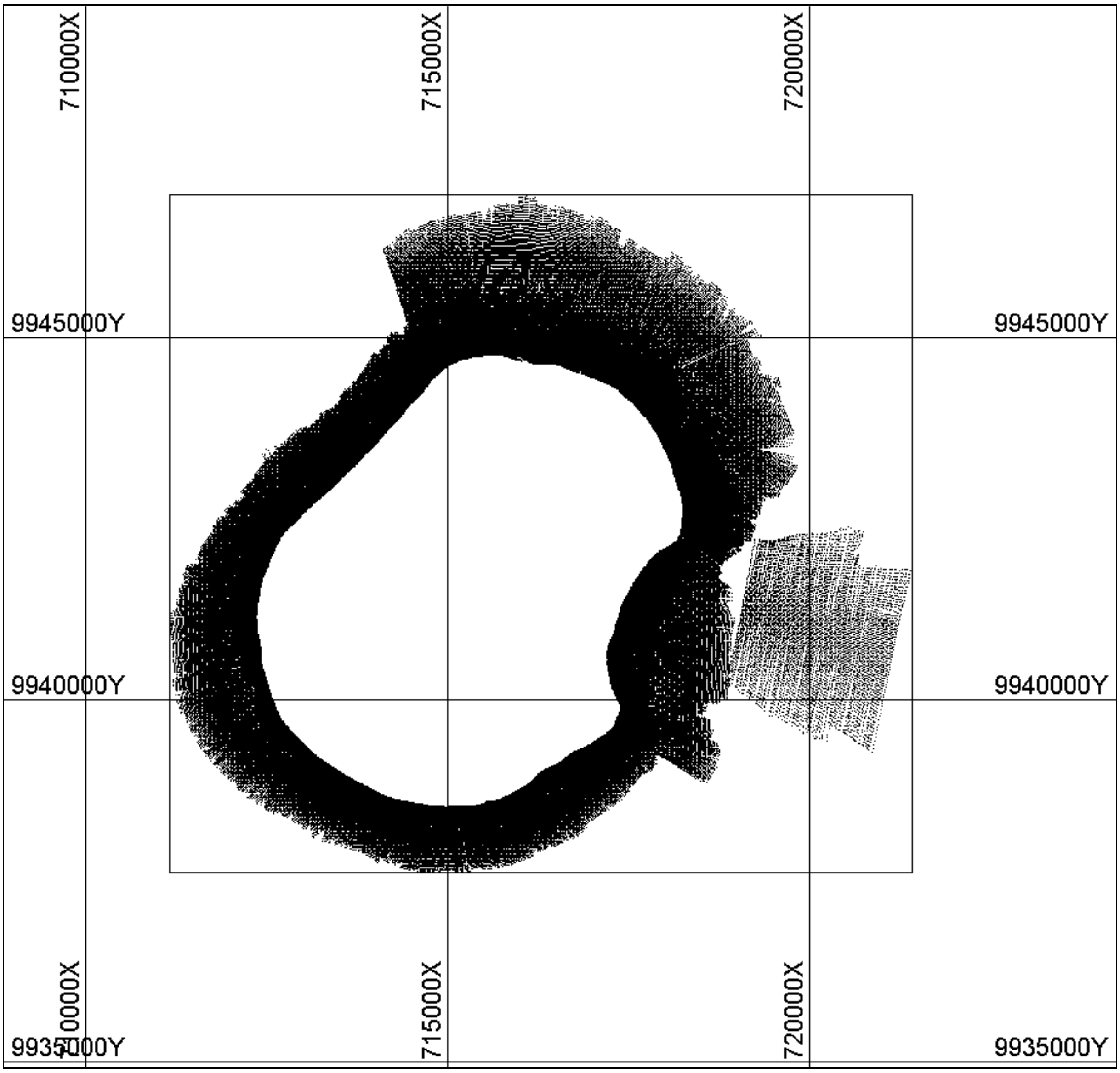


Figure A2.2. Map showing the SOPAC/EU MBES coverage for Nauru. Data density varies from a few metres in the shallow nearshore to tens of metres in the deeper offshore area.

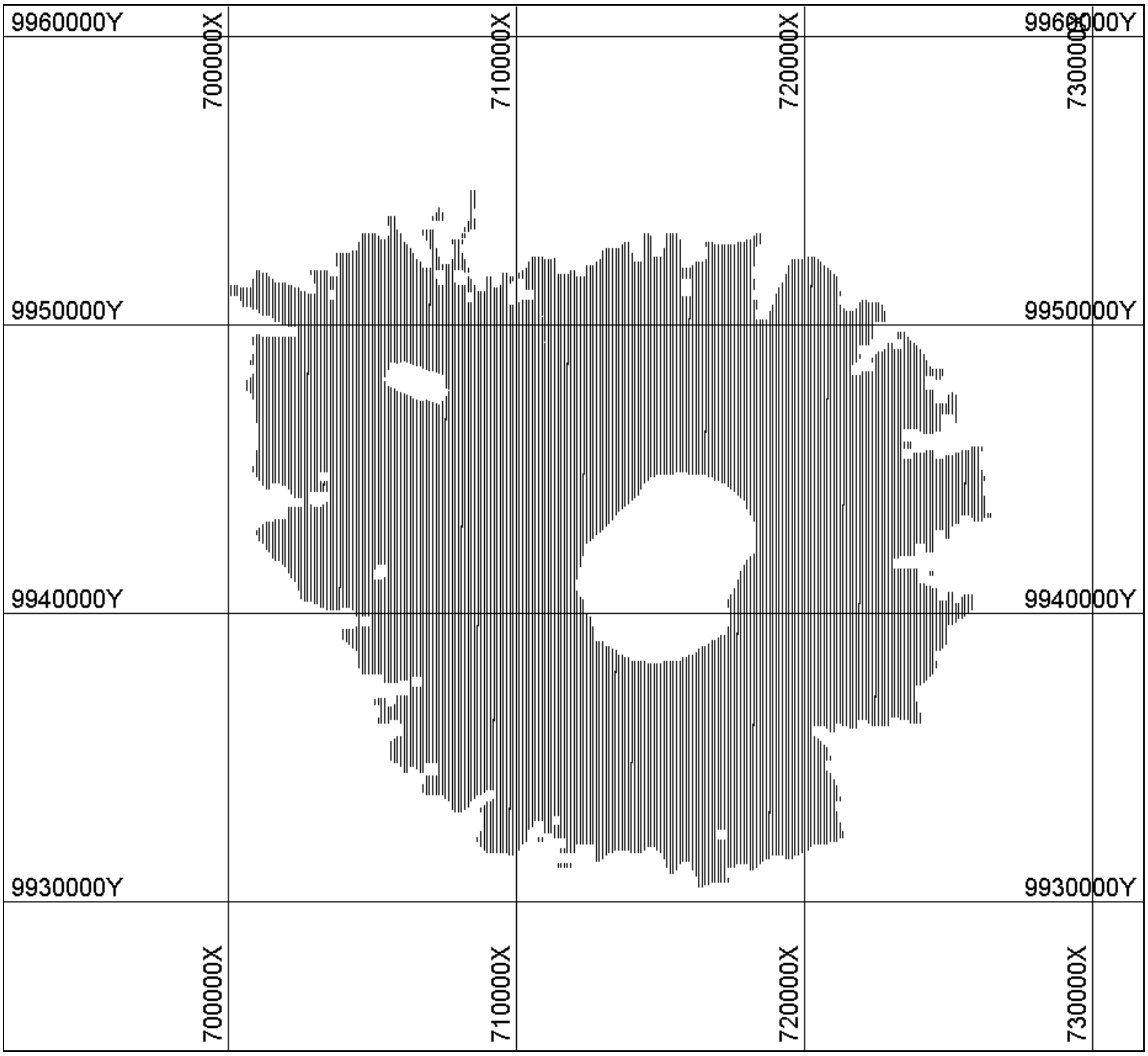


Figure A2.3. Map showing the NOAA bathymetry included in this report. Data density is 111 m in the W-E direction and 11 m in the N-S direction. RV Ronald H. Brown*, Nauru99 campaign, SeaBeam system.*

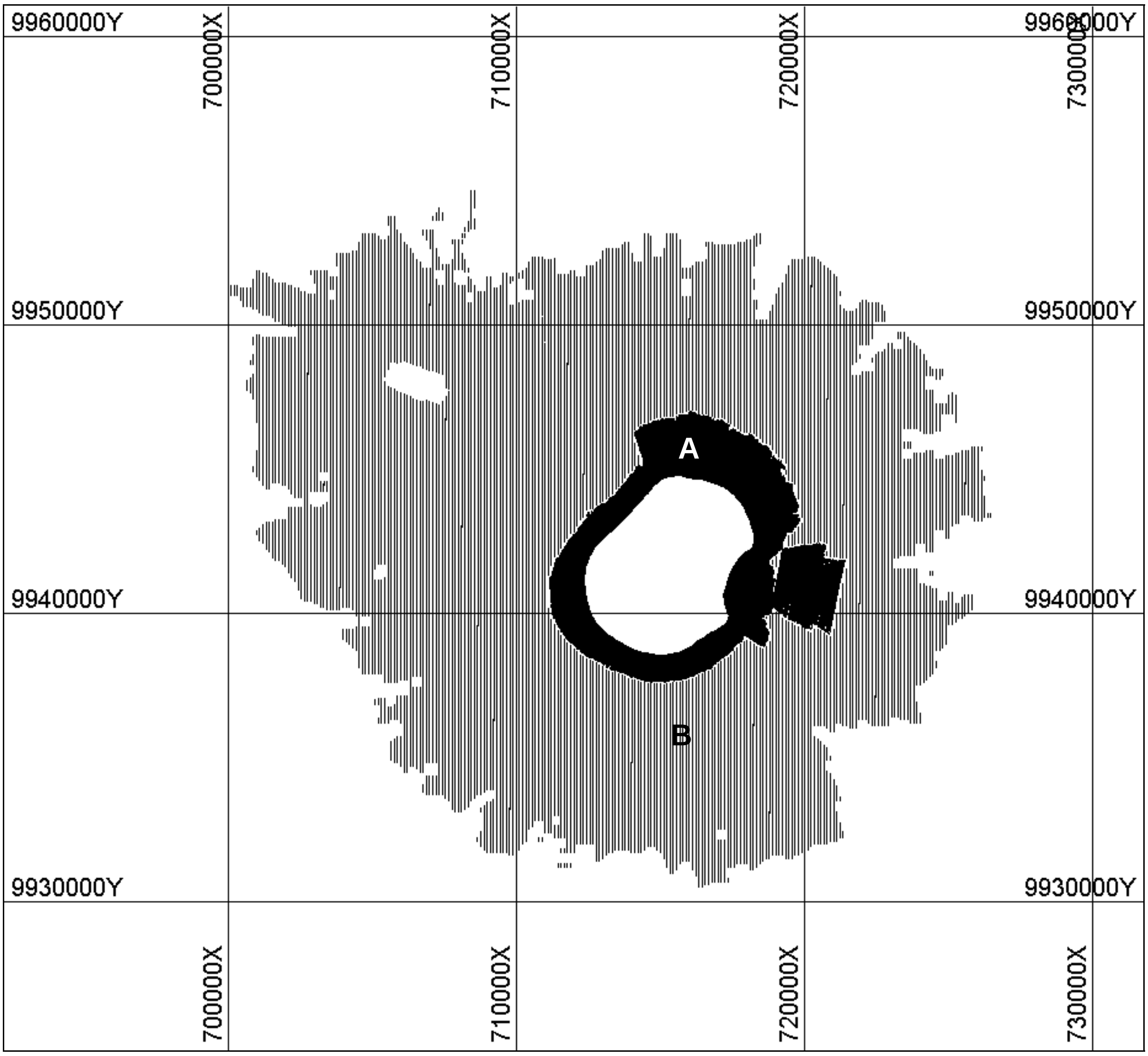
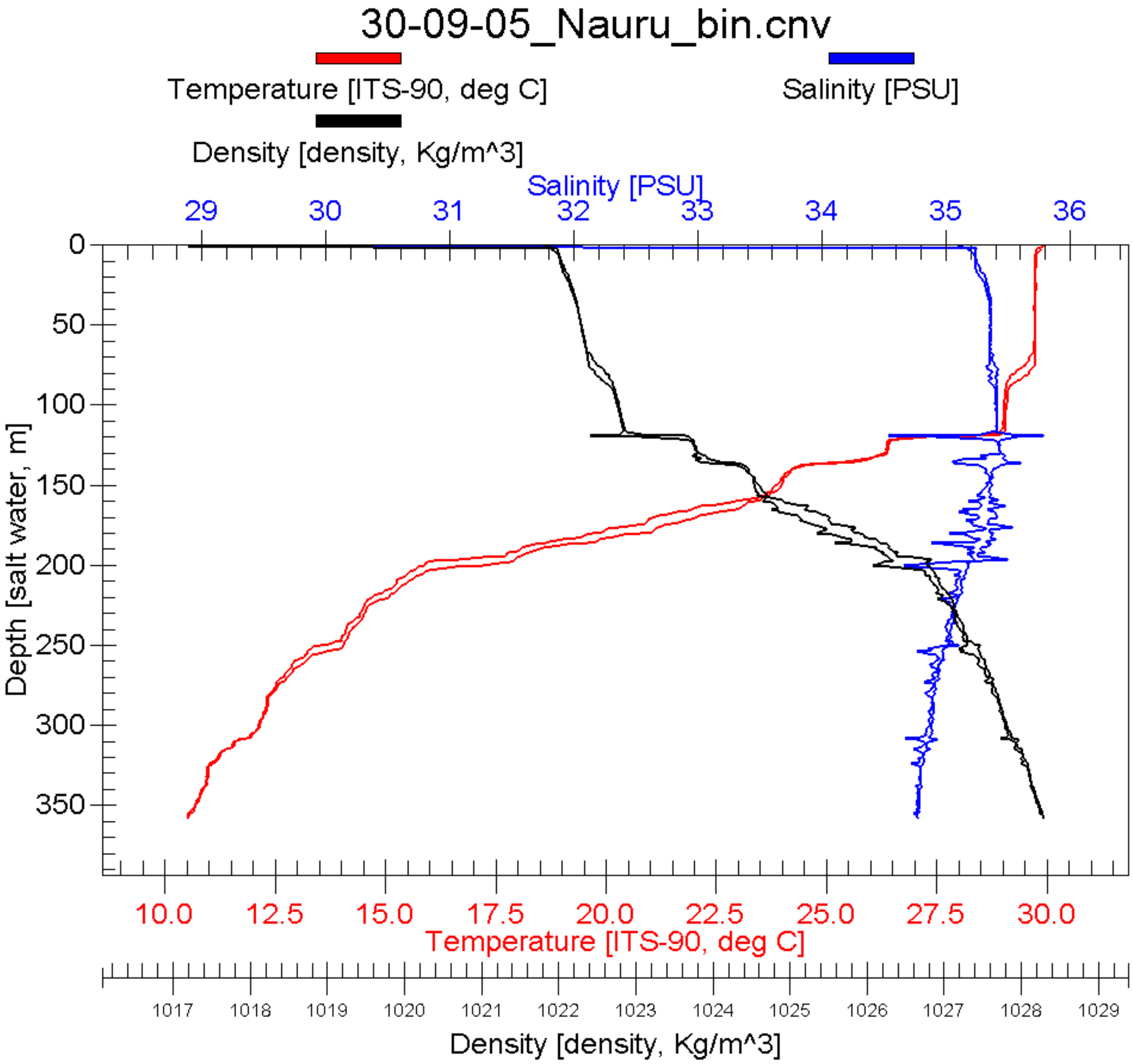


Figure A2.4. Map showing the merged bathymetric data sets from (A) SOPAC/EU and (B) NOAA, as shown in Figure A2.2 and Figure A2.3, respectively. Note the differences in data density, and the 100 m buffer zone created between data sets to avoid intersecting sounding points.

Appendix 3 – CTD Profile Data



Appendix 4 – High-Resolution A0 Charts, Nauru Bathymetry

Charts are available from SOPAC, and can be downloaded from its website (www.sopac.org). Full size is 841 x 1189 mm. (Low-resolution A4 representation follows.)

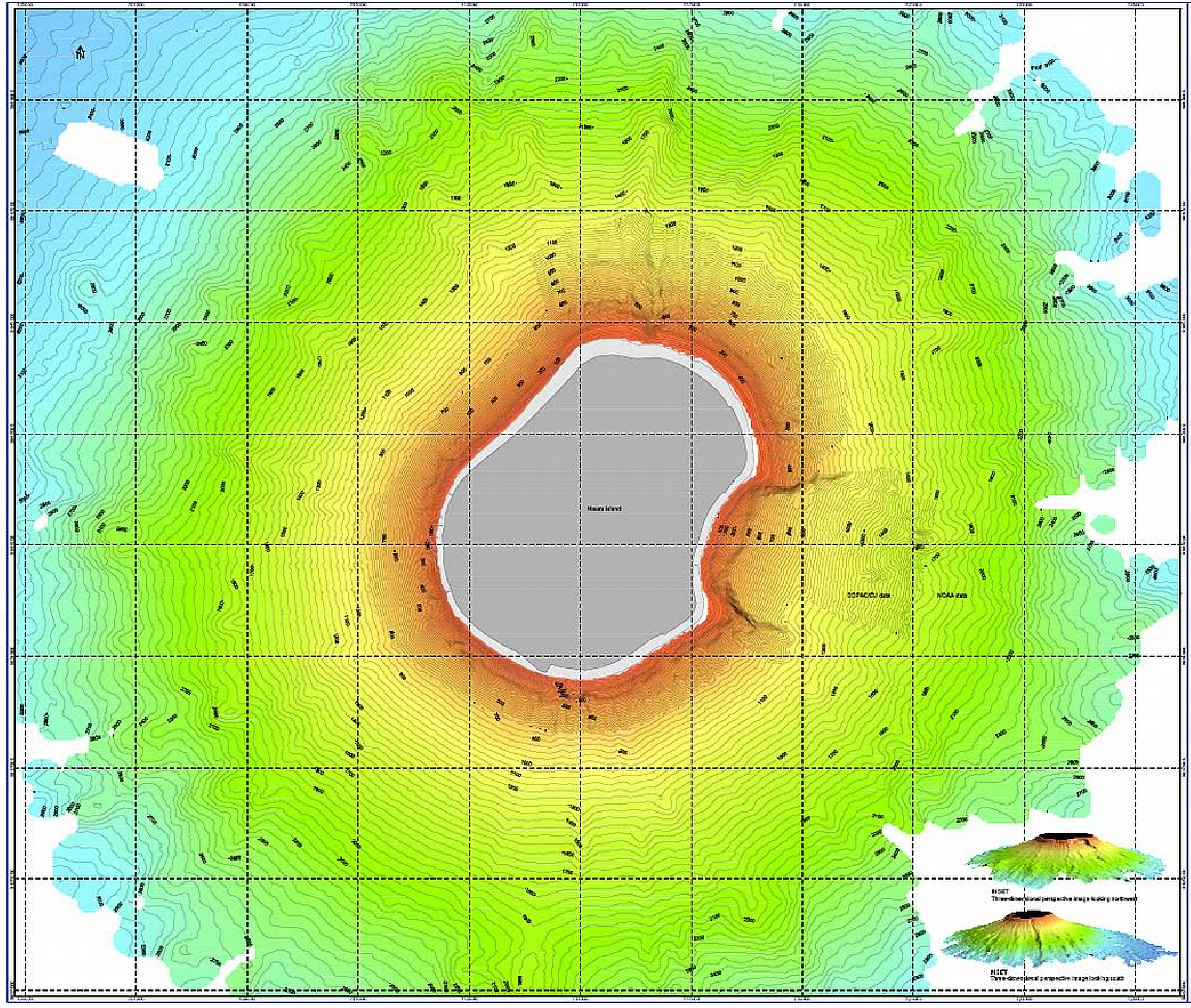
Chart No	Title	Scale	Drawing No.
1	Nauru, Bathymetry	1 : 25 000	ER116.1

Appendix 5 – SOPAC Multibeam Online Line Log

Operating Parameters
Model:
Sample rate:
Final Bin Size:
Remarks:

Hypack Project Name: Nauru
Country: Nauru
Area: Nauru
Vessel: Summer Spirit
MBES System: 8160
Positioning: Stand alone GPS

Date	Location	Line No.	Time		Fix		HDG	SPD	Filename (.HSX)	Log File (.LOG)	Line QC	Comments / Online changes
			SOL	EOL	SOL	EOL						
30/09/2005	Nauru		07:23	07:33	1	24	289	7.5	000_0723		JK	approach
	Nauru		08:57	10:32	25	227	336	7	000_0857		JK	Hydrolab
	Nauru		10:32	12:18	228	451	342	7	000_1032		JK	Hydrolab
	Nauru		12:18	12:40	452	500	309	7	000_1218		JK	Hydrolab
	Nauru		12:49	13:42	501	613	67	7	000_1249		JK	
	Nauru		13:49	13:50	614	617	39	7	000_1349		JK	gap fill
	Nauru		13:58	15:09	618	763	207	6.5	000_1325		JK	
	Nauru		15:19	15:47	764	823	114	6.5	000_1519		JK	
	Nauru		15:52	15:53	824	829	89	8	000_1551		JK	departure



LEGEND

Bathymetric contours shown at 20 metre intervals (SOPAC/EU data), and 50 metre intervals (NOAA data)

Boundary delineating SOPAC/EU data (nearshore) and NOAA data (offshore)

Land area

Reef platform

Colour Banding
Bathymetry
Metres

200
700
1200
1700
2200
2700
3200
3700
4200

NOTES

Nearshore data by SOPAC/EU:

Observed soundings have been reduced to Nauru Island Datum defined as 0.220 m below LAT, 1.3906 m below mean sea level (MSL 1993-1994), and 7.2630 m below the fixed height of Benchmark NAU 1

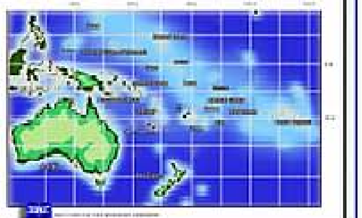
Date of Survey	30/06/2005
Acquisition system	Reson Seabat 8160 multibeam echosounder
Collection software	Hypack 4.3
Processing software	Hypack 4.3A
Data presentation	Surfer 8.03
Survey vessel	M.V. Summer Spirit

Offshore data by NOAA:

Observed soundings have no vertical datum collected by R.V. R.H. Brown, presumably in 1999

NOT TO BE USED FOR NAVIGATION

LOCATION



GEODETIC INFORMATION

Geodetic datum	WGS84
Ellipsoid	WGS84
Projection	UTM Zone 58 South
Horizontal positioning	Stand alone GPS

SCALE

Scale 1 : 25 000

0 500 1000 1500 2000
Metres

A2 Original

PROJECT TITLE

SOPAC

PACIFIC ISLANDS APPLIED GEOSCIENCE COMMISSION
Private Mail Bag, GPO, Suva, Fiji Islands
www.sopac.org

SOPAC/EU Project
Reducing Vulnerability of Pacific ACP States

DRAWING TITLE

NAURU

BATHYMETRY

Drawn by: Ashishika Sharma. Report Reference: ER118. Drawing No.: ER118.1