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ASTER bathymetry in computational fluid dynamic simulation of Rongelap Atoll hydrodynamics, Marshall Islands

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Abstract. ASTER green, red and near infra-red (NIR) imagery with a resolution on the order of handheld GPS echo soundings was calibrated to model bathymetry of Rongelap Atoll to a depth of 10 meters. The ASTER model was converted into of depth contours at 1, 2, 4, 8, and 16 meters. Beyond that depth nautical charts and echo soundings were used to model bathymetry. The combined result was a bathymetric digital elevation model of Rongelap Atoll and surrounding seas, which was converted to X,Y,Z file and for input into reverse engineering software. The reverse engineering software then created a NURBS (Non-Uniform Rational B-Spline) surface model, for input into the finite element meshing program GAMBIT (ANSYS Fluid Dynamics International). These data were then ordered in volumetric and substrate surface elements of coral reefs and input to the FLUENT computational fluid dynamics (CFD) package. Bluelink (Australian Bureau of Meteorology and CSIRO) was used to apply boundary conditions, and results are hydrodynamic charts of the atoll. The resulting map of substrate shear stress at Rongelap is displayed in Figure 2. Figure 2 Benthic shear stress of Rongelap Atoll.

Key words: Atoll, Hydrodynamics, Remote Sensing.

Introduction

Peterson, et al. (2005) argued that computational fluid dynamics are needed to classify regions of benthic shear stress in coral reef ecosystems. That study also presented correlated biological and physical observations from Rongelap Atoll to demonstrate the importance of benthic shear stress in defining habitat suitability in coral reef ecosystems.

The present paper seeks to map Rongelap's previously uncharted waters and to improve our understanding of hydrodynamics in, through, and around the vicinity of this atoll.

Four different datasets were fused to create the digital elevation model employed in the present paper with the ultimate goal to simulate the hydrodynamics of Rongelap Atoll. A nautical chart (Fig. 1) was available, which was copied from Japanese Navy surveys 1917 and 1922 under League of Nations Mandate, and since reprinted by the US government. This chart only covers a fraction of the atoll, and the coordinates of this chart are not WGS84. Likely the original surveys were based on sextant placement of a granite monument (with Japanese characters) found in the main settlement of Rongelap. To this day numerous digital charting products have misplaced every single feature of Rongelap Atoll by at least a mile, but Reston (2007) used the ASTER scene to adjust the chart with WGS84 graticule marks.

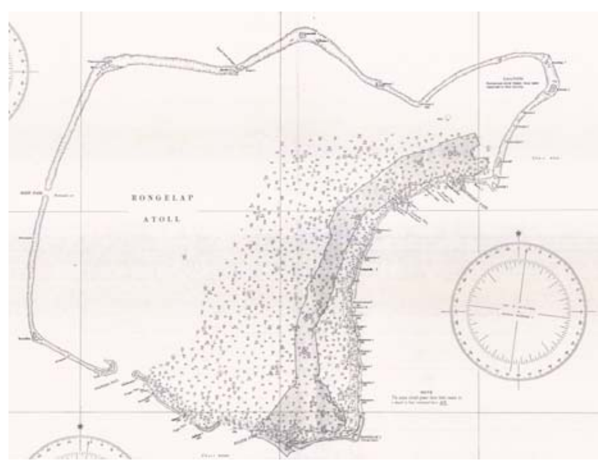

Figure 1: Latest published chart of Rongelap (evidently a copy of Japanese surveys 1917 and 1922, Alele Public Library, Majuro).

Another bathymetric dataset available were coincident GPS tracklogs and echo-sounding during reef surveys (Pinca et al. 2002; Peterson et al. 2005). This largely filled in the western side of Rongelap lagoon, but failed to reach the far northeast corner.

The deepwater bathymetric dataset used in the present study was from Hein et al. (2007). But parts of Rongelap were not covered by the digital elevation model, and little information exists on shallow waters that flood over reef crests. Reefs are by their nature too shallow for navigation, and so not fathomed on nautical charts. Thus, remote sensing is a useful tool to estimate depth. We used an ASTER scene, of which we excluded the blue (B) band, but included the green (G), red (R) and near infrared (NIR) for determination of the land/water interface.

Bathymetric modelling utilises a variety of techniques comparing green and blue wavelengths (Reston 2007). For the present study, visible green only was used for bathymetric calculation, and as a consequence, was expected to yield results with lesser depth penetration than those expected with the inclusion of visible blue data.

Reston (2007) constructed a linear regression model using sub-samples of validation data derived from GPS tracked echo soundings (Pinca, et al. 2002, and Peterson 2005), and historic nautical charts to predict depth from the calibrated ASTER data. Land and breaking water was identified using the NIR band, and assigned a threshold value of 0.5m to preclude their inclusion in the bathymetric calculation, while bathymetry deeper than 20m was assigned that value as a constant. Depth penetration of green light in the ASTER Rongelap scene is approximately 20 metres, exceeding expectations, owing to the clarity and optical penetrative characteristics of the Marshall Islands waters.

An example of results from the southeast corner of the ASTER scene is detailed in Figures 1 and 2, being the main island of Rongelap.

Approximately 15% cloud coverage exists in the NE quadrant of the ASTER image. These have been masked by manually editing contours extracted from the pseudocolour water depth DEM

Material and Methods (CFD modelling)

The ASTER-derived contours of shallow water bathymetry were then kriged together with the nautical chart soundings, NRAS survey track logs and the deep water regional bathymetry to produce a continuous DEM seafloor surface of the Rongelap Atoll region as an ASCII Raster file with 300 meter resolution, and then converted into x,y,z point-cloud data in comma separated values (CSV). The seafloor DEM as CSV was then converted into NURBS (Non-Uniform Rational B-Spline, with algorithms of Bézier & de Cateljau (Farin 2002) surface using ProEngineer "reverse engineering" toolbox (Fig. 4).

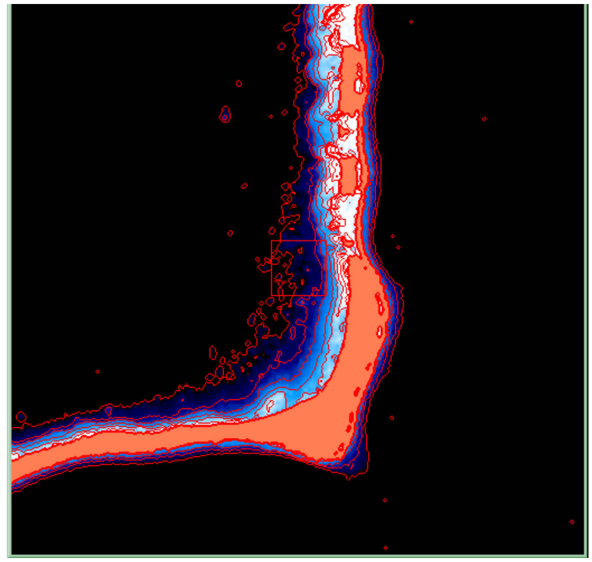

Figure 2: False colour water depth overlain by 0, 2, 4, 6, 8, 10, 12, 14, 16, 18, and 20 m contours in SE corner of Rongelap Atoll.

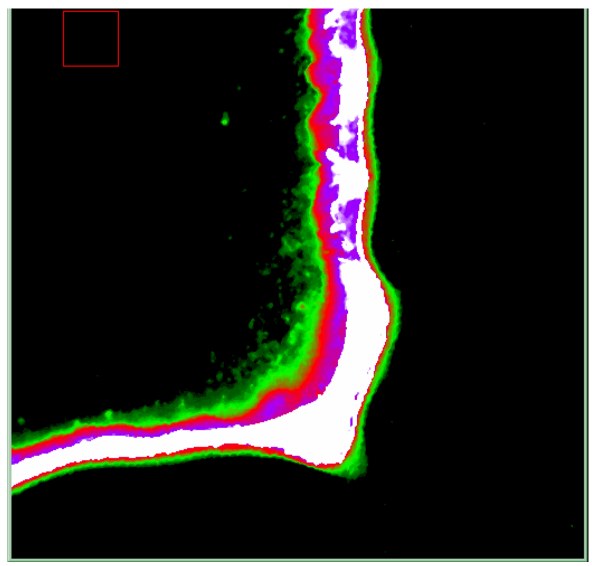

Figure 3: Pseudocolour water depth DEM product in SE corner.

The NURBS surface represents the complex seascape of coral reefs bounding the lower face of the fluid flow problem, while the upper surface is given a fixed-lid approximation as determined by sea level as the air/water interface. This modelling approach suits extensive submergent reefs such as Micronesia with only "small islands" set in trade wind circulated seas. The NURBS surface was saved in IGES format and then imported into the meshing program GAMBIT (Figure 5) for development of the CFD domain.

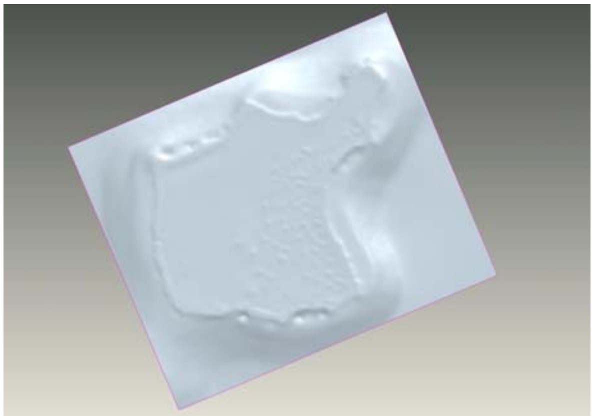

Figure 4: Screenshot from ProEngineer of Rongelap NURBS.

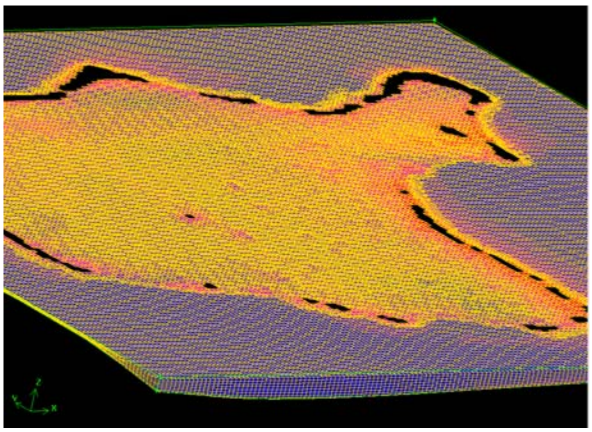

Figure 5: Screenshot from GAMBIT mesh generation for Rongelap model. Slicing ten meters into the domain, islands and reef flats appear as voids, but there is flow allowed to go over all areas.

The computation mesh was then read into Fluent software with the imposition of boundary conditions referencing the BLUELink conditions of Figure 6:

- Sea surface – wall allowed to slip with specified wind shear 10 knot (5 m/s) tradewind driven current flow east>west stress vector (1,0,0) [Pa]
- Sea floor – no-slip wall and with shear stress reactions evaluated by CFD
- Sea to north, south, and west – Current from east (-.2,0,0) [m/s] velocities from BLUELink (www.bom.gov.au).
- Sea to west – low pressure exhaust [-100Pa].
- turbulent intensity ~30% of mean flow based on BLUELink> 1st-14th Jan 2000.
- hydraulic radius ~ 1000m depth of ocean.

BLUELink> is described by Brassington (2007).

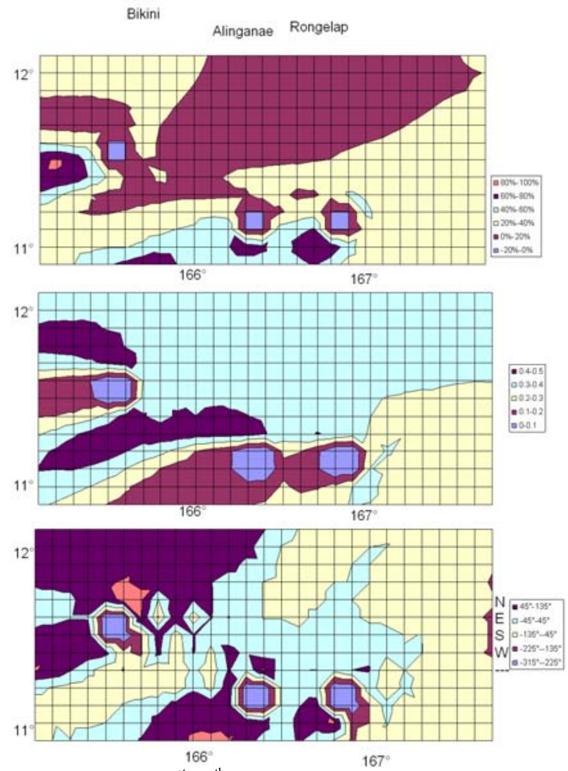

Figure 6: BLUELink> 1st-14th Jan 2000 conditions around Bikini-Alinganae-Rongelap region. Turbulent Intensity above, mean speed middle, and direction below.

The turbulent viscosity model is realizable k-epsilon with the following features:

- Turbulent intensity $I = u'/\bar{U}$ = rms/speed
- Eddy scale ~ 7% of hydraulic diameter
- Turbulent kinetic energy $k = {}^3/_2 \cdot (\text{speed} \cdot I)^2$
- Turbulent dissipation rate $\varepsilon = 2.35\ k^3/_2/L$
- Turbulent viscosity $\mu_t = 0.09\ \rho\ k^2/\varepsilon$

Results

Preliminary benthic shear stress results of simulation are illustrated in Fig. 7. The strong red spot on the main island of Rongelap is fictional, since this island is not actually covered by the present sea level. This result could be masked out with polygons of land, to provide a Geographical Information System product of the CFD simulation.

Other important products of the CFD model could be the larval connectivity matrix between each reef, but this has not yet been produced for Rongelap Atoll.

Figure 7: Resulting benthic reaction [Pa].

Discussion

BLUELink> provides real-time 11km resolution hydrodynamic conditions throughout the Indo-Pacific. This provides an opportunity to model local areas of interest, such as Rongelap Atoll. BLUELink> provides seaward and airside boundary conditions to CFD modelers. It is then a problem of nesting mesoscale models within the regional model provided by BLUELink.

Convergence has generally improved in solutions where u,v,w components of flow are specifically mapped at the seaward boundaries of the CFD model. It has proven better to also define the western seaward boundary with explicit velocity components rather than an exhaust condition.

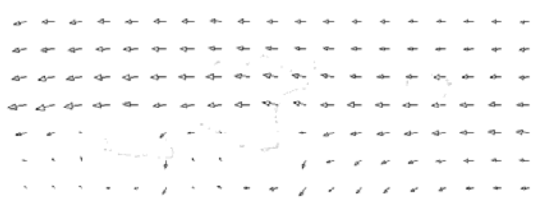

Figure 8: BLUELink> surface vectors around Alinganae and Rongelap Atolls 1st January 2000. Many layers of the ocean, and many years of daily data are available by automated web queries.

The DEM will be extended around Rongelap to match the BLUELink grid illustrated in Figure 8. The DEM model of Hein et al. (2007) extends well into these deeper waters, and so it will not be difficult to resample it to produce a larger NURBS domain. For hydrodynamic modeling of the Rongelap region, the hypothesis is that the critical factor to determine flow through atoll systems is the shallowness of the reef flats, where red and green light penetration is amply suited to measure bathymetry. Figure 9 illustrates the thin sheet of fast moving flow over a reef flat.

Figure 9: Flow over Rongelap reef flat, particle tracked with GPS.

The CFD model is yet to be validated with the GPS tracklogs illustrated in Figure 9. In that particular fieldwork exercise a tide guage was set up to establish a staging-curve of flow over the reef flat. An echo-sounder provided the depth of water, while the gps measure the velocity of surface water flow of a snorkler following slightly positively buoyant floater illustrated in Figure 10. Thus each tracklog has a coincident depth log, and so the two integrate volumetric flow over the reef flat per cross unit width.

Figure 10: Flow over reef flat, tracked with echo-sounding GPS

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