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High-resolution depth and coastline over major atolls of South China Sea from satellite altimetry and imagery

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ABSTRACT

Current bathymetric models for the South China Sea (SCS) are largely based on predicted depths from gravity and sparse single-beam echo-sounder measurements. Such models lack high-resolution coastlines and shallow-water bottom features around atolls and islands. This study refines the gravity field of the SCS using sea surface heights from measurements of satellite altimeter Geosat/GM, ERS-1/GM, Jason-1/GM and the original Cryosat-2. A new one-minute gravity anomaly grid is determined. The modeled gravity anomalies show a 6-mgal RMS discrepancy with shipborne measurements in shallow waters. An altimeter-only bathymetric model is derived from the new gravity grid by the gravity-geological method that uses the latest global and regional models of the ocean depth and marine gravity as a priori knowledge. The new model outperforms current SCS bathymetric models and is accurate to 100 m, based on comparison with multi-beam depth measurements. Optical images from IKONOS-2, QuickBird-2, GeoEye-1, WorldView-1-2 and -3, are rectified and digitized to derive the zero (coastline) and 20-m depth contours (reef lines) around 44 atolls, which are integrated with the altimeter-only depths, giving significantly improved accuracies and spatial resolutions in modeled depths. The improvement percentages of coastlines by the satellite imagery range from 50% to 97% at 41 of the 44 atolls. We establish a webpage for free access to the optical and depth images, and the depth and gravity grids. We will continue to update satellite images, altimeter-derived gravity grids and bathymetric models over major atolls of the SCS.

1. Introduction

The South China Sea (SCS) is a semi-open sea surrounded by the mainland China, Taiwan, Vietnam, Malaysia, Indonesia and the Philippines. Its complex seafloor topography is the result of several stages of rifting, volcanic activities and seafloor spreading (Taylor & Hayes, 1980, 1983). The bottom of the SCS has continental shelves around the margin with a deep-sea basin in the center. There are scattered seamounts, atolls and islands over both the deep and shallow waters. Recent progress in satellite altimetry and gravity field has led to improved global bathymetric models that also give refined depth resolutions in the SCS (Andersen, 2010; Sandwell, Müller, Smith, Garcia, & Francis, 2014). In addition, the latest altimeter-derived marine gravity and bathymetric models show hidden undersea tectonic features in the SCS (Sandwell et al., 2014; Hwang & Chang, 2014).

In general, altimeter-derived depths are limited by spatial resolutions at 16–60 km (Smith & Sandwell, 1997; Sandwell et al., 2014), and contain large uncertainties over shallow waters. In areas close to the coast, seamount and atoll, the data density and data quality of altimeter measurements become quickly degraded. Here estimating gravity and depth from altimetry becomes challenging compared to open oceans. To compromise between depth quality and spatial resolution, filtering of initial depths must be employed to remove outliers and obtain reasonable depth estimates in such areas. For example, Marks and Smith (2007) used filters with various widths to best recover seamounts from altimeter-derived gravity in the western Pacific Ocean. They concluded that seamounts with smaller characteristic radius (<14 km) may be well resolved by linear filtering. Despite altimeter data refining and gravity filtering, it remains unlikely to recover zero depths (coastlines) from altimeter and ship data alone.

The deficiency in the estimation of shallow-water depths from altimetry and ship gravimetry may be removed by merging them with shoreline data from other sources. For example, Hwang (1999) used GMT-defined zero depths to constrain the altimeter-derived ocean depths in the SCS on a $2' \times 2'$ grid. Amante and Eakins (2009) refined

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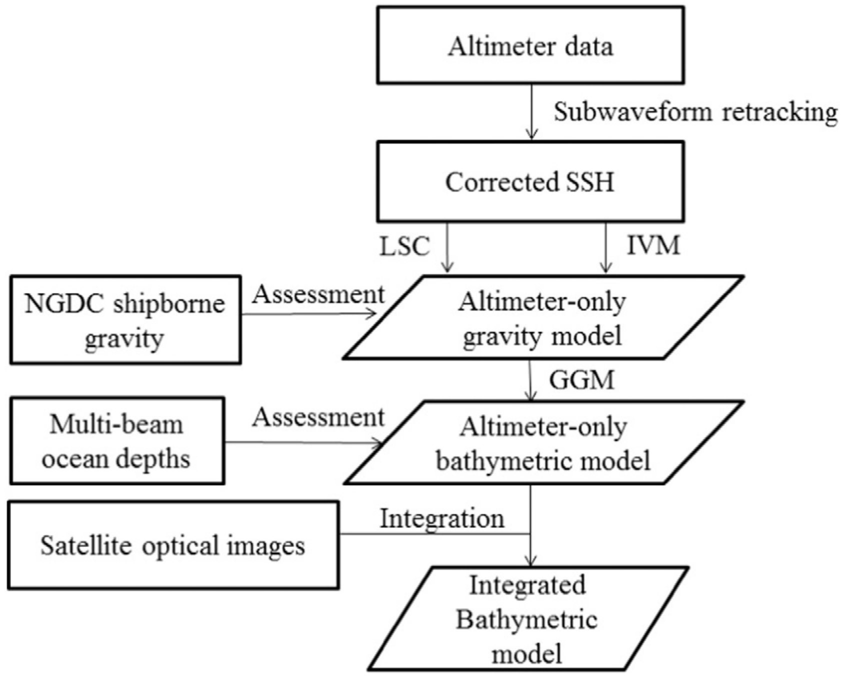

Fig. 1. A flowchart showing the data processing and modeling in this paper.

depths of the initial ETOPO1 model between 0 to 500 m using world vector shorelines from the Global Self-consistent Hierarchical High-resolution Geography Database (GSHHS). Because the GSHHS shorelines have a nominal spatial resolution of 50–500 m (Wessel & Smith, 1996), they cannot be used to identify atolls with sizes less than 100 m. The depths of General Bathymetric Chart of the Oceans (GEBCO) (http://www.gebco.net/) are given on a $30'' \times 30''$ grid, and GEBCO's zero depths are also derived from the GSHHS shorelines. GEBCO is unable to identify the borders of atolls with a radius less than 500 m. On the other hand, because the coordinate frames used in historical shoreline databases may be different from the frames for modern satellite mapping technologies such as GPS, the resulting shorelines are subject to errors (Hwang, 1999).

An important technique to render accurate shorelines around atolls is satellite imagery. Recent technological progress has significantly increased the accuracy and spatial resolution of shorelines defined by satellite images. Lyzenga (1978) was the first to use satellite imagery to estimate depths. Subsequent investigations were made by Lyzenga (1981), Benny and Dawson (1983), Philpot (1989), Ibrahim and Cracknell (1990), Baban (1993), Melsheimer and Chin (2002), and Kao et al. (2009). With a spatial resolution finer than 1 m, optical images from missions such as IKONOS and Quickbird have been used to refine depths and shorelines around atolls (Stumpf, Holderied, & Sinclair, 2003; Su, Liu, & Heyman, 2008; Conger, Hochberg, Fletcher, & Atkinson, 2006; Mishra, Narumalani, Rundqulst, & Lawson, 2006; Lyons, Phinnemail, & Roelfsemaemail, 2011). Predicting depths from optical image is largely based on attenuation of sunlight in water, reflectance of water bottom, and property of water. The results form open publications show that a maximum depth of about 20 m can be obtained using optical images.

This paper explores the potential of satellite altimetry and satellite imagery in recovering high-resolution depths over shallow waters of the SCS (range: 0°–22°N and 100°–126°E). Specifically, our objective is to (1) derive a best gravity model and a best altimeter-only bathymetric model in the SCS using all possible and refined satellite altimeter data, and then (2) increase the accuracy and spatial resolution of depths at major atolls of the SCS by integrating altimeter-derived depths and coastlines from satellite optical images. An atoll is typically over an extinct volcano and may contain a dry part (island) and submerged reefs. Accurate depths around an atoll are highly important for precise hydrodynamic interpolation of ocean tide, prevention of maritime hazards and study of its marine ecosystem. Fig. 1 shows a flowchart of data processing and modeling in this paper. First, ranges from all altimeters other than Cryosat-2 are corrected by waveform retracking. The improved ranges are then used to compute sea surface heights (SSHs) to construct gravity grids in the SCS by least-squares collocation (LSC)

Table 1
Statistics of differences between altimeter-derived gravity and shipborne gravity at two depth ranges (unit: mgal).

Model	Data	Retrack	Method	Depth	Mean	Std.	Max.	Min.
Case 1	ERS-1	No	IVM	All	−0.2	9.2	71.9	−97.4
	Geosat			<500 m	−0.1	9.9	62.4	−64.8
Case 2	ERS-1	Yes	IVM	All	−0.1	6.3	81.9	−91.9
	Geosat			<500 m	−0.3	7	58.6	−57.6
Case 3	ERS-1	Yes	LSC	All	−0.1	5.9	80.1	−87.9
	Geosat							
	Jason-1			<500 m	−0.5	6.7	61.9	−56.8
	Cryosat-2							
Case 4	ERS-1	Yes	IVM	All	0	6	80.6	−90.4
	Geosat							
	Jason-1			<500 m	−0.2	6.8	61.3	−57.3
	Cryosat-2							
DTU10	ERS-1	–	–	All	0	6.1	79.9	−84.6
	Geosat			<500 m	−0.4	7.1	54.3	−58.6
Sandwell V23.1	ERS-1	–	–	All	−0.5	6	82.7	−83
	Geosat							
	Envisat							
	Jason-1			<500 m	0.6	7.7	57.7	−61.1
	Cryosat-2							