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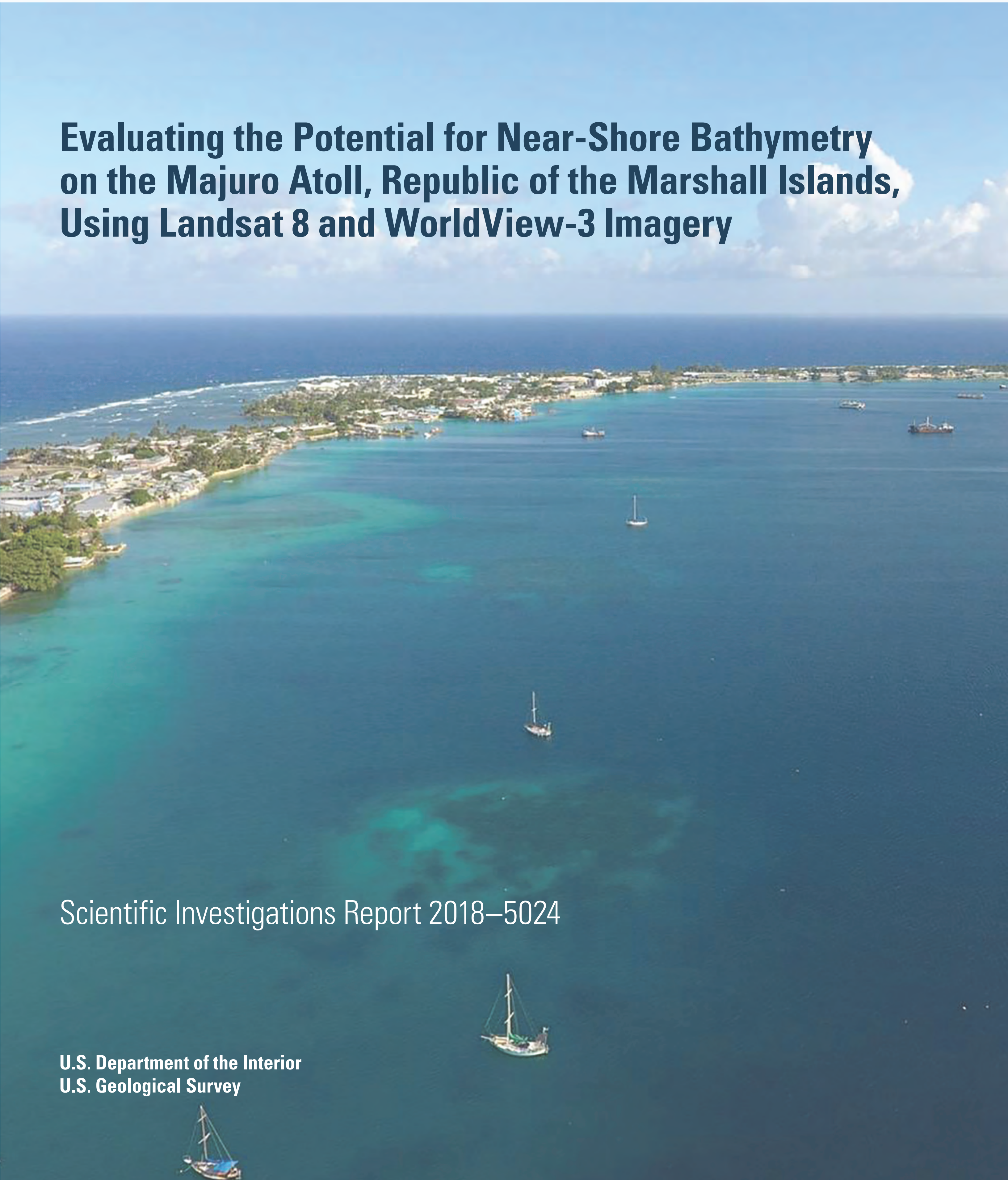
Evaluating the Potential for Near-Shore Bathymetry on the Majuro Atoll, Republic of the Marshall Islands, Using Landsat 8 and WorldView-3 Imagery



Scientific Investigations Report 2018–5024

U.S. Department of the Interior
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Cover. Majuro, Majuro Atoll, Republic of the Marshall Islands, surrounded by the shallow lagoon (foreground) and the deep Pacific Ocean (background). Image taken by Maria Kottermair, Geospatial Coordinator, Pacific Islands Climate Science Center at the University of Guam.

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	U.S. Survey foot (ft)
meter (m)	1/0.3048	international foot (ft)
meter (m)	1.094	yard (yd)
kilometer (km)	0.621	mile (mi)

Datum

Horizontal coordinate system is Universal Transverse Mercator (UTM) Zone 59 North referenced to International Terrestrial Reference Frame 2008 (ITRF2008).

Vertical datum is referenced to Local Mean Sea Level (LMSL).

Abbreviations

ACOMP	atmospherically corrected
CHARTS	Compact Hydrographic Airborne Rapid Total Survey
CMGP	Coastal and Marine Geology Program
CoNED	Coastal National Elevation Database
DNC	Digital Nautical Chart
DOI	Department of the Interior
L8	Landsat 8
lidar	light detection and ranging
LMSL	local mean sea level
ME	mean error
MLWS	mean low water springs
NAVOCEANO	Naval Oceanographic Office
NGA	National Geospatial-Intelligence Agency
NOAA	National Oceanic and Atmospheric Administration
NIR	near-infrared
PI–CSC	Pacific Islands Climate Science Center
RMSE	root mean square error
SDB	satellite-derived bathymetry
SfM	Structure from Motion

SOPAC	South Pacific Applied Geoscience Commission
SWIR	shortwave infrared
TBDEM	topobathymetric digital elevation model
UAS	Unmanned Aircraft Systems
USGS	U.S. Geological Survey
UTM	Universal Transverse Mercator
VPF	Vector Product Format
WV-3	WorldView-3

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Abstract

Satellite-derived near-shore bathymetry (SDB) is becoming an increasingly important method for assessing vulnerability to climate change and natural hazards in low-lying atolls of the northern tropical Pacific Ocean. Satellite imagery has become a cost-effective means for mapping near-shore bathymetry because ships cannot collect soundings safely while operating close to the shore. Also, green laser light detection and ranging (lidar) acquisitions are expensive in remote locations. Previous research has demonstrated that spectral band ratio-based techniques, commonly called the natural logarithm approach, may lead to more precise measurements and modeling of bathymetry because of the phenomenon that different substrates at the same depth have approximately equal ratio values. The goal of this research was to apply the band ratio technique to Landsat 8 at-sensor radiance imagery and WorldView-3 atmospherically corrected imagery in the coastal waters surrounding the Majuro Atoll, Republic of the Marshall Islands, to derive near-shore bathymetry that could be incorporated into a seamless topo-bathymetric digital elevation model of Majuro. Attenuation of light within the water column was characterized by measuring at-sensor radiance and reflectance at different depths and calculating an attenuation coefficient. Bathymetric lidar data, collected by the U.S. Naval Oceanographic Office in 2006, were used to calibrate the SDB results. The bathymetric lidar yielded a strong linear relation with water depths. The Landsat 8-derived SDB estimates derived from the blue/green band ratio exhibited a water attenuation extinction depth of 6 meters with a coefficient of determination R^2=0.9324. Estimates derived from the coastal/red band ratio had an R^2=0.9597. At the same extinction depth, SDB estimates derived from WorldView-3 imagery exhibited an R^2=0.9574. Because highly dynamic coastal shorelines can be affected by erosion, wetland loss, hurricanes, sea-level rise, urban development, and population growth, consistent bathymetric data are needed to better understand sensitive coastal land/water interfaces in areas subject to coastal disasters.

Introduction

Satellite-derived near-shore bathymetry (SDB) remote sensing research uses ocean optics to estimate near-shore bathymetry using passive multispectral satellite imagery, such as Landsat 8 (L8) or DigitalGlobe WorldView-3 (WV-3) (Gesch and others, 2016; Pe'eri and others, 2014; 2016a; 2016b; Stumpf and others, 2003). Active sensors, such as light detection and ranging (lidar) or sound navigation and ranging (sonar), have been used to collect bathymetric data; however, mapping islands in the Pacific Ocean with green laser lidar sensors aboard a small, fixed-wing aircraft is expensive. Because surface vessels often cannot collect soundings safely while operating close to the shore, satellite imagery has potential to be a more cost-effective means for mapping near-shore bathymetry to assess vulnerability to natural hazards in low-lying atolls in the northern tropical Pacific.

In the scientific literature, the most common method used to derive bathymetry from satellite imagery is an optimization approach using spectral band ratio-based techniques, more commonly called the ratio of natural logarithm approach (Dierssen and others, 2003; International Hydrographic Organization, Intergovernmental Oceanographic Commission, 2016; Pe'eri and others, 2014; 2016a; 2016b; Stumpf and others, 2003). This empirical method may lead to more precise measurements and modeling of bathymetry because different substrates at the same depth have approximately equal ratio values (Legleiter and Overstreet, 2012). A study by Pe'eri and others (2014) indicated that, based on the assumption that the water column is uniformly mixed, the ratio of two bands, such as blue/green, will maintain a near-constant attenuation value that is the difference of the diffuse attenuation coefficient values at two different wavelengths. The concept underlying the ratio transform approach is that bottom radiance of one band will decay faster with depth as compared to the other band. As a result, the ratio between the two bands will vary with depth (Pe'eri and others, 2014). The logarithm of the band-ratio approach accounts for the exponential attenuation of light in the water column; therefore, the image-derived quantity, or the change in ratio between bands, is affected more by depth than by bottom reflectance (Stumpf and others, 2003). Thus, a linear relation between water depth and reflectance, relative radiance, or raw digital numbers in one or more spectral bands is commonly used for SDB (Legleiter and others, 2012; Pe'eri and others, 2014; 2016a; 2016b).

According to Stumpf and others (2003), the use of satellite imagery might be the only viable way to synoptically characterize either extensive or remote coral reef environments because of incomplete or spatially limited bathymetric data or difficulty obtaining soundings in remote reef areas. Stumpf and others (2003) indicated that high spatial resolution is required due to the relatively small horizontal spatial features in remote coral atoll locations; therefore, medium resolution (30 meters [m]) and high-resolution (1.6 m) satellite imagery were used to estimate SDB for the Majuro Atoll coral reef environment.

Background

In the northern tropical Pacific Ocean, Majuro is a large coral atoll consisting of a central narrow landmass and a set of small perimeter islets that are part of the Republic of the Marshall Islands (fig. 1). The Pacific Ocean on the exterior of the atoll and the lagoon within its interior consist of unconsolidated and consolidated carbonate sediment, steep slopes, and deep bathymetry. Information about the bathymetry of the shallow waters surrounding the coral atoll is not well known (Kruger and Kumar, 2008). This low-lying atoll is extremely vulnerable to sea-level rise, tsunamis, storm surge, and coastal flooding that could affect the sustainability of the infrastructure, groundwater, and ecosystems (Palaseanu-Lovejoy and others, 2017a; 2017b).

The highest natural elevation of the Majuro Atoll is estimated at only 3 m above sea level at the community of Laura on the western part of the atoll (fig. 1). The capital city of Majuro, on the eastern edge of the atoll, has the largest population. The island community of Djarrit is on the northeast part of the atoll. The lack of high-resolution topographic data has been identified as a critical data gap for climate vulnerability and adaptation efforts and for high-resolution inundation modeling for atoll nations (Helweg and others, 2014; Palaseanu-Lovejoy and others, 2017b). Therefore, near-shore bathymetry was derived from the best available L8 and WV-3 satellite imagery to integrate into a 1-m topobathymetric digital elevation model (TBDEM) for the Coastal National Elevation Database (CoNED) Majuro Atoll to support storm- and tide-induced flood modeling (Danielson and others, 2016; Palaseanu-Lovejoy and others, 2017b; Thatcher and others, 2016). The Majuro TBDEM development was a collaboration among the U.S. Geological Survey (USGS) CoNED Applications Project, Department of the Interior (DOI) Pacific Islands Climate Science Center (PI-CSC), USGS Coastal and Marine Geology Program (CMGP), University of Guam, University of Hawaii at Mânoa, National Oceanic and Atmospheric Administration (NOAA) National Geodetic Survey, the Republic of the Marshall Islands Office of Lands and Survey, College of the Marshall Islands, Directorate of Civil Aviation Republic of the Marshall Islands, and the Marshall Islands Conservation Society (Palaseanu-Lovejoy and others, 2017a; 2017b).

Data Used for Satellite-Derived Bathymetry

U.S. Geological Survey Landsat 8 Satellite Imagery

The L8 Operational Land Imager Level-1, 16-bit, relatively cloud-free multispectral imagery acquired at nadir on March 1, 2016, was downloaded from USGS EarthExplorer in georeferenced GeoTIFF format in Universal Transverse Mercator (UTM) Zone 59 North projection (U.S. Geological Survey, 2016b). The L8 satellite orbits the Earth at an altitude of 705 kilometers (km) (438 miles [mi]). The satellite images a swath width of 185 km (115 mi) in a sun-synchronous, near-polar orbit with a revisit frequency of 16 days (U.S. Geological Survey, 2016a). The multispectral bands used in the SDB process were coastal band 1 (0.43–0.45 micrometer [µm]), blue band 2 (0.45–0.51 µm), green band 3 (0.53–0.59 µm), red band 4 (0.64–0.67 µm), and the shortwave infrared (SWIR)-1 band 6 (1.57–1.65 µm) (U.S. Geological Survey, 2016a). The Landsat satellites have continuously acquired space-based images of the Earth's land surface, providing data that serve as valuable resources for a number of applications; for example, the L8 Operational Land Imager contains a deep blue band for coastal areas and shallow water observations that is useful for SDB research (U.S. Geological Survey, 2016a).

DigitalGlobe WorldView-3 Satellite Imagery

DigitalGlobe WV-3 Level-2A atmospherically corrected (ACOMP) over water, 16-bit, multispectral imagery acquired at 13.9° mean off-nadir angle on March 30, 2016, was obtained from DigitalGlobe in georeferenced TIF format in UTM Zone 59 North projection (DigitalGlobe, 2016). The DigitalGlobe WV-3 satellite orbits the Earth at an expected altitude of 617 km (383 mi), imaging a swath width at nadir of 13.1 km (8 mi) with a revisit frequency of less than 1.0 day at 40° N latitude and 4.5 days at 20° off nadir or less (DigitalGlobe, 2016). The multispectral bands used in the SDB process were blue band 2 (0.45–0.51 µm), green band 3 (0.51–0.58 µm), and the near-infrared (NIR2) band 8 (0.86–1.04 µm).

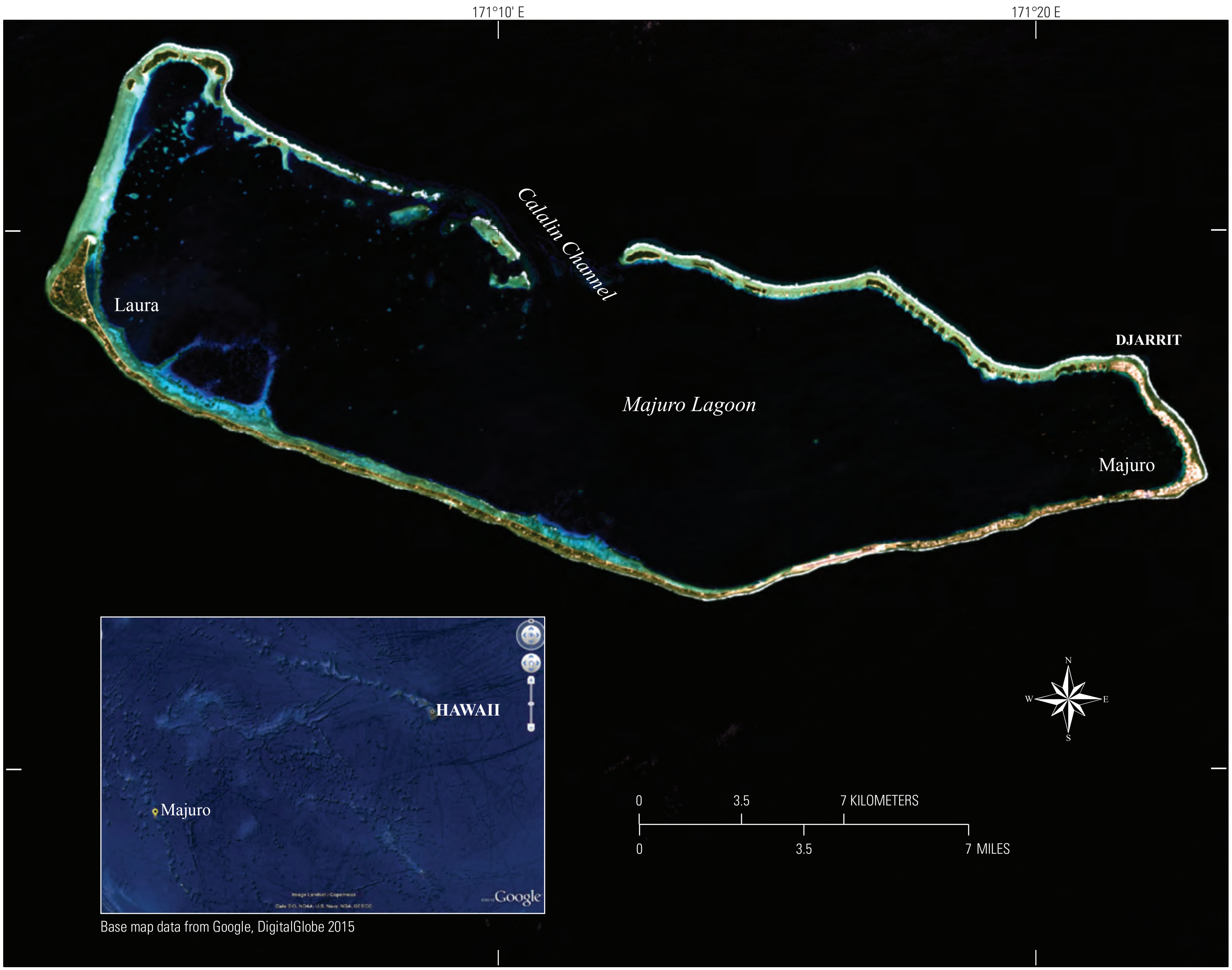

Figure 1. Majuro Atoll, Republic of the Marshall Islands. Landsat 8 imagery of the Majuro Atoll acquired on March 1, 2016, symbolized as red/green/blue bands 4, 3, 2, natural color.

Compact Hydrographic Airborne Rapid Total Survey Bathymetric Lidar

An airborne hydrographic survey of the Majuro Calalin Channel, Republic of the Marshall Islands (fig. 1), was completed by the U.S. Naval Oceanographic Office (NAVOCEANO) on April 25, 2006, using the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) aboard a Beachcraft King Air 200 at a wavelength of 532 nanometers (nm). All point data measurements were referenced to World Geodetic System 1984 (WGS84) ellipsoid in meters and vertically referenced to mean low water springs (MLWS) (Naval Oceanographic Office, 2006a, 2006b). According to the NAVOCEANO Report of Survey, the CHARTS system collects bathymetric lidar data that meet the U.S. Army Corps of Engineers survey standard of 30 centimeter (cm) root mean square error (RMSE) (Naval Oceanographic Office, 2006b). The CHARTS bathymetric lidar data were obtained from NAVOCEANO to use as control points for SDB calibration (Naval Oceanographic Office, 2006a).

National Geospatial-Intelligence Agency Nautical Charts

The North Pacific Ocean Republic of the Marshall Islands Majuro Atoll Nautical Chart 81782 was obtained from the National Geospatial-Intelligence Agency (NGA) as a georeferenced .pdf (National Geospatial-Intelligence Agency Maritime Safety Office, 2011) and was converted to a georeferenced .tiff (raster format) to use as reference information in a geographic information system. Additionally, the Digital Nautical Chart (DNC) 12 Library for the Majuro Atoll was obtained from NGA as Vector Product Format (VPF) that contained hydrographic sounding feature classes (National Geospatial-Intelligence Agency Maritime Safety Office, 2017). The DNC 12 VPF soundings were from U.S. Navy surveys of 1944 and 2006 (National Geospatial-Intelligence Agency Maritime Safety Office, 2011; 2017) and were initially used for reference information and for SDB calibration testing.

Methods

Satellite-Derived Bathymetry Vertical Profile Estimates

The band ratio technique (Dierssen and others, 2003; International Hydrographic Organization, 2016; Pe'eri and others, 2014; 2016a; 2016b) was applied to L8 at-sensor radiance imagery and WV-3 ACOMP imagery in the coastal waters surrounding the Majuro Atoll, Republic of the Marshall Islands. Esri ArcMap and Harris Geospatial ENVI software were used to subset and process the L8 and WV-3 imagery to the Majuro Atoll extent. The L8 and WV-3 raw imagery values were converted to floating point values. An inflection point was determined on a spectral response curve between the land and water using the L8 SWIR–1 band 6 (1.57–1.65 µm) and WV-3 NIR2 band 8 (0.86–1.04 µm) to mask out the land part of the study area. The WV-3 SWIR–1 band at 3.74-m resolution was not used to determine the inflection point in the WV-3 imagery because the resolution differed from the WV-3 multispectral bands at 1.6-m resolution. The WV-3 NIR2 band (8) was used instead because it had a similar wavelength as the L8 SWIR–1 band (6).

Attenuation of light within the water column was characterized by measuring at-sensor radiance or reflectance at different depths and calculating an attenuation coefficient based on the ratio of L8 bands blue (2)/green (3) and L8 bands coastal (1)/red (4). The WV-3 SDB attenuation coefficient was based on the blue (2)/green (3) band ratio (eq. 1). The concept underlying the ratio transform approach is that bottom radiance of one band will decay faster with depth than the other band. As a result, the ratio between the two bands will vary with depth (Pe'eri and others, 2014).

This ratio of natural logarithms method, as shown in equation 1, calculates relative vertical profile estimates using multispectral satellite bands from which the diffuse attenuation coefficients are computed (Dierssen and others, 2003; Pe'eri and others, 2014; Stumpf and others, 2003). Depth estimates are derived using this equation as in the Stumpf and Pe'eri approach:

$$z = m_1 \left(\frac{\ln\left(L_{obs}\left(\lambda_i\right)\right)}{\ln\left(L_{obs}\left(\lambda_j\right)\right)} \right) - m_0 \tag{1}$$

where

- z is the relative vertical profile depth estimates,
- m_1 and m_0 are the gain (tangent of the slope angle) and offset (intercept), respectively, that are empirically determined,
- ln is the natural logarithm ratio of the attenuation between observed radiance estimated (reflectance for WV-3 ACOMP)
- $L_{obs}(\lambda i)$ observed radiance of the Landsat blue band or observed reflectance of the WV-3 coastal band, and
- $L_{obs}(\lambda j)$ observed radiance of the Landsat green band or observed reflectance of the WV-3 red band.

The resulting values represent relative SDB vertical profile estimates that needed to be calibrated to obtain actual depth values.

Calibration of Vertical Profile Estimates

The CHARTS bathymetric lidar points were projected to UTM Zone 59 North projection. A linear regression was completed between the projected CHARTS bathymetric lidar values and the relative vertical profile estimates to derive an optical depth for inferring bathymetry, or extinction depth; an *R*-squared; and the regression line equation, which was applied to the relative vertical profiles estimates for calibration purposes. Optically deep values beyond the extinction depth then were removed.

Because the goal of this research was to generate near-shore SDB that could be integrated into a 1-m TBDEM (Danielson and others, 2016), the calibrated vertical profile SDB estimates were adjusted from chart or bathymetric lidar values (MLWS) to map datum (Local Mean Sea Level [LMSL]) by applying an adjustment value of 1.022 m derived from the Majuro International Airport benchmark tied to the local tidal benchmark (Naval Oceanographic Office, 2006a; 2006b). This adjustment was applied to achieve a consistent datum with topographic elevation data that are part of the CoNED Majuro Atoll TBDEM.

Validation of Vertical Profile Estimates

This research investigated the potential for using medium- and high-resolution satellite imagery (L8 and WV-3) to derive near-shore bathymetry for the Majuro Atoll, Republic of the Marshall Islands. The ratio of natural logarithms methodology required ancillary bathymetric data to calibrate the SDB estimates (Pe'eri and others, 2016a). The only available CHARTS bathymetric lidar data were collected in the Calalin Channel (Naval Oceanographic Office, 2006a; 2006b), a shipping channel in the northern part of the Majuro Atoll (fig. 1); therefore, part of the CHARTS bathymetric lidar data was used to calibrate the SDB estimates, and the remaining bathymetric lidar data were used for validation purposes (fig. 2).

Because the CHARTS bathymetric lidar data were available only in the upper-middle part of the atoll shipping channel, high-resolution (WV-3) SDB profiles were derived in this location to determine SDB profiles from atmospherically corrected satellite imagery over water using the ratio of natural logarithm approach.

The position errors between the measured values (CHARTS bathymetric lidar) and the estimated vertical profile SDB values were described using the mean error (ME), mean absolute error, standard deviation, and RMSE. The L8-derived SDB was validated against more than 16,000 bathymetric lidar points, and the WV-3-derived SDB was verified by more than 9,000 bathymetric lidar points.

Results

The calibrated SDB vertical profile estimates are shown in figure 3. The WV-3 blue/green ratio SDB results, shown in the central part of the Majuro Atoll, are derived from the only location where satellite imagery was atmospherically corrected over water (fig. 3, green). For the remaining part of the atoll, the blue/green ratio was applied to medium-resolution satellite imagery (L8) (fig. 3, red and light blue). In the western part of the atoll, the blue/green ratio SDB results were less than optimal because of very shallow reef flats. Therefore, the coastal/red ratio was applied, which resulted in reasonable near-shore bathymetric estimates (fig. 3, light blue).

Position errors between the measured values (CHARTS bathymetric lidar) and the estimated vertical profile SDB are shown in table 1. There is a positive bias in the SDB data of 0.947 m (mean error) for the L8 blue/green band ratio SDB, 0.285 m for the L8 coastal/red band ratio, and 0.867 m for the WV-3-derived SDB (table 1). The L8 blue/green ratio was used to derive near-shore bathymetry for most of the atoll lagoon excluding depth values below the 6-m extinction depth. The L8 coastal/red ratio was better suited to derive near-shore bathymetry north of Laura because of the very shallow reef flats, and the WV-3 blue/green ratio was used to derive near-shore bathymetry for the central part of the atoll near the Calalin Channel (fig. 1) (Palaseanu-Lovejoy and others, 2017b).

For bathymetry in general, the vertical accuracy depends on water depth, water conditions, such as waves, tide, and water transparency, errors introduced by the instrument and the mode of deployment, cloud cover, atmospheric conditions, and the angle off nadir (Goodman and others, 2008; Lee, 2012; Pe'eri and others, 2014; 2016b). All these potential sources of errors may contribute to the positive bias in the SDB. The SDB data were split into two depth intervals, 0–4 m and 4–6 m (SDB extinction depth) (table 2), so the depth errors could be further investigated.

For L8 (blue/green and coastal/red ratios) and WV-3 (blue/green ratio) SDB, the ME for depths up to 4 m are -0.199, -0.913, and 1.253 m, respectively, whereas the ME for depths greater than 4 m up to the optical extinction depth are 1.004, 0.336, and 0.810 m, respectively. These results indicate bias in both depth interval data, but also that L8-derived SDB has a bimodal distribution as shown in the violin plot in figure 4.

A violin plot is, to a large extent, a box plot that incorporates information about the underlying distribution of the data, adding a rotated kernel density plot on each side (Hintze and Nelson, 1998; National Institute of Standards and Technology, 2015). In comparison, a box plot shows only summary statistics such as mean/median and interquartile ranges, whereas the violin plot shows the full distribution of the data. The difference is particularly useful when the data distribution is multimodal, such as for L8 data. A split violin plot shows two different groupings for a certain category. In this study, for each satellite sensor and band ratio (L8 blue/green, L8 coastal/red, and WV-3 blue/green), the split violin plot shows the density distributions, box plots, and outliers of validation errors by depth (deep, from -6 to -4 m; and shallow, from -4 to 0 m) (fig. 4). The data distribution shows a conspicuous bimodality in the L8 data, with positive bias for deeper waters (-6 to -4 m) and negative bias for shallow waters (-4 to 0 m), whereas WV-3 data are positively biased in both depth categories.

This is one of the first attempts to use SDB for shallow near-shore bathymetry in the context of a tropical carbonate

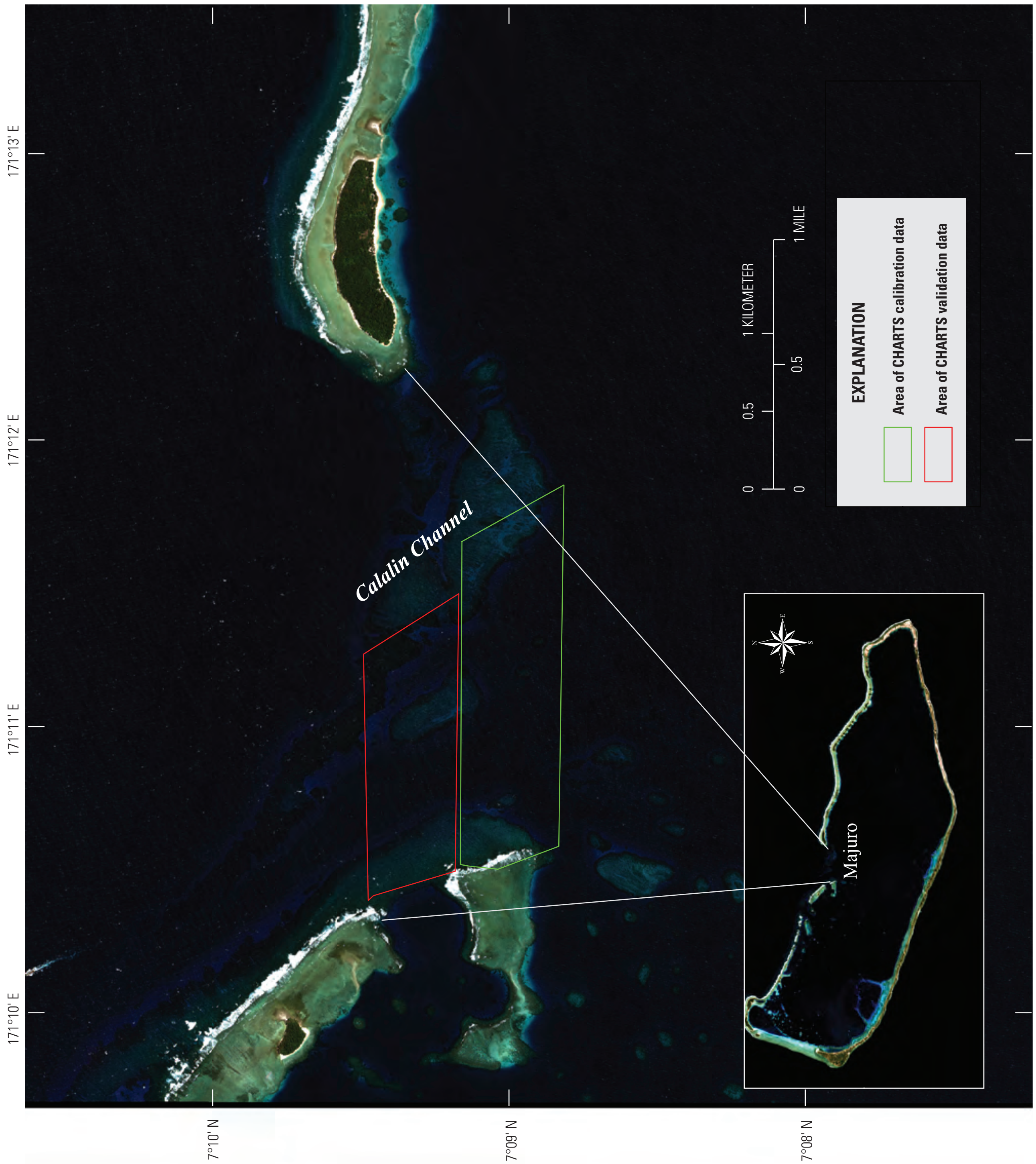

Figure 2. Areas of Compact Hydrographic Airborne Rapid Total Survey (CHARTS) bathymetric light detection and ranging calibration and validation data.

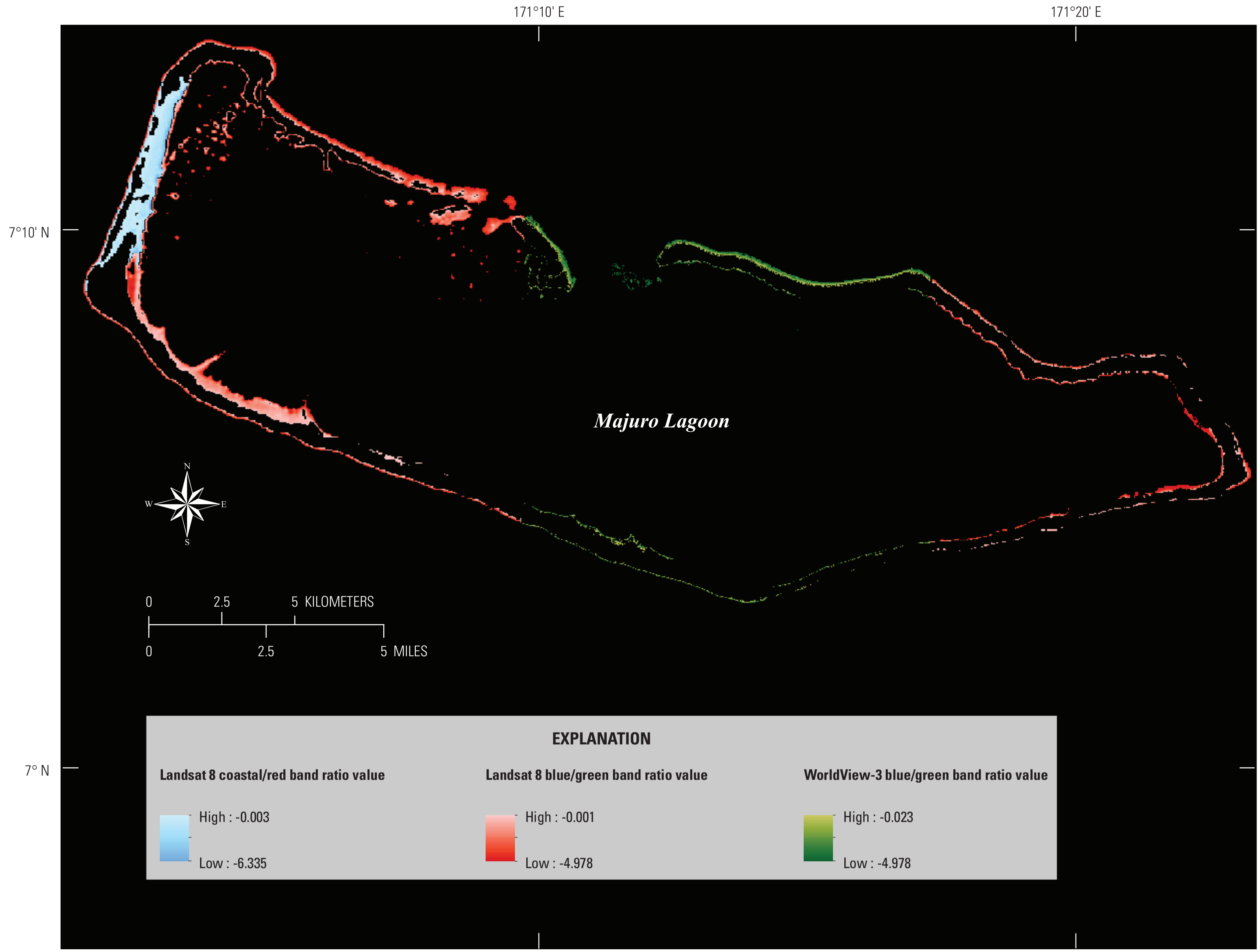

Figure 3. Medium- (Landsat 8) and high-resolution (WorldView-3) satellite-derived bathymetry for the Majuro Atoll, Republic of the Marshall Islands.

Table 1. Validation measurement results for satellite-derived bathymetry (SDB) estimates and Compact Hydrographic Airborne Rapid Total Survey (CHARTS) bathymetric light detection and ranging (lidar) data.

Ratio of natural logarithms	Compact Hydrographic Airborne Rapid Total Survey bathymetric light detection and ranging points	Mean error (meters)	Mean absolute error (meters)	Standard deviation (meters)	Root mean square error (meters)
Landsat 8 satellite-derived bathymetry blue/green band ratio	16,941	0.947	0.980	0.486	1.065
Landsat 8 satellite-derived bathymetry coastal/red band ratio	3,090	0.285	1.408	1.451	1.478
WorldView-3 satellite-derived bathymetry blue/green band ratio	9,632	0.867	0.919	0.697	1.112

Table 2. Error metrics for the satellite-derived bathymetry (SDB) accuracy assessments.

Depth	Errors compared to Compact Hydrographic Airborne Rapid Total Survey bathymetric light detection and ranging	Landsat 8 satellite-derived bathymetry blue/green ratio (nadir)	Landsat 8 satellite-derived bathymetry coastal/red ratio (nadir)	WorldView-3 satellite-derived bathymetry blue/green ratio (off-nadir-view angle 13.9 degrees)
Overall	Compact Hydrographic Airborne Rapid Total Survey bathymetric light detection and ranging points	16,941	3,090	9,632
	Area (percent of total atoll)	2.43 percent	0.67 percent	0.46 percent
	Mean error (meters)	0.947	0.285	0.867
	Mean absolute error (meters)	0.980	1.408	0.919
	Root mean square error (meters)	1.065	1.478	1.112
0–4 m	Compact Hydrographic Airborne Rapid Total Survey bathymetric light detection and ranging points	801	125	1,239
	Mean error (meters)	-0.199	-0.913	1.253
	Mean absolute error (meters)	0.479	1.038	1.327
	Root mean square error (meters)	0.608	1.231	1.640
4–6 m	Compact Hydrographic Airborne Rapid Total Survey bathymetric light detection and ranging points	16,140	2,965	8,393
	Mean error (meters)	1.004	0.336	0.810
	Mean absolute error (meters)	1.005	1.423	0.859
	Root mean square error (meters)	1.082	1.488	1.011

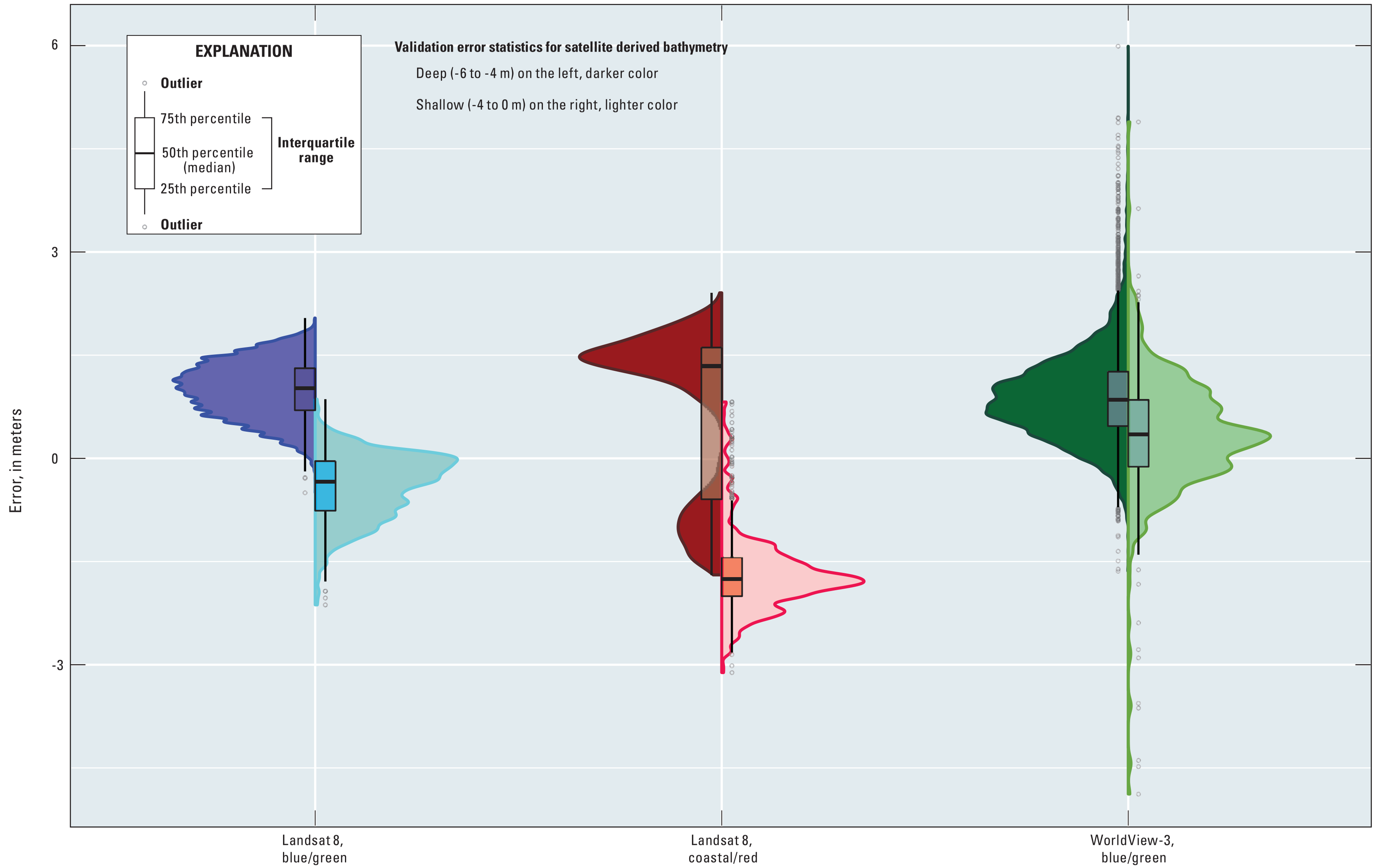

Figure 4. Split violin plots showing satellite-derived bathymetry (SDB) validation errors in meters compared to the Compact Hydrographic Airborne Rapid Total Survey (CHARTS) data. The data are categorized by satellite type and band ratio used (Landsat 8 blue/green, Landsat 8 coastal/red, WorldView-3 blue/green), and each category is split by depth. The deep group (-6 to -4 m depth) is plotted on the left side for each category in darker colors (dark blue, dark red, dark green), and the shallow group (-4 to 0 m depth) is plotted on the right side for each category in lighter colors (cyan, light red, lime green).

platform. A depth-related adjustment may be used to overcome the bias; however, from the SDB results, it is not clear if the adjustment would be only depth dependent or if the adjustment would be location dependent as well. For this reason, the SDB data were not further amended before integration into the Majuro, Republic of the Marshall Islands, TBDEM (fig. 5).

Discussion

There are numerous factors to consider when analyzing the bias that was evident in the SDB accuracy assessment compared to the CHARTS bathymetric lidar data. Although Stumpf and others (2003) indicated high spatial resolution, such as WV-3 imagery, is required to derive SDB because of the relatively small horizontal spatial scales in remote coral atoll locations, Lee (2012) indicated that a high off-nadir acquisition angle of WorldView imagery may contribute to derived depth errors because more off-nadir view angles proved to have lower correlation values to the actual "true" bathymetry data. Although the WV-3 imagery was collected at an off-nadir angle, the L8 imagery was collected at nadir; therefore, the off-nadir angle may not contribute to the errors in the L8 SDB. Cloud cover will affect ocean optics, thus leaving void spaces in the SDB profile estimates; however, all the L8 and WV-3 satellite images used in this research were cloud free.

Atmospheric conditions are another concern when deriving SDB. The WV-3 imagery that was atmospherically corrected was obtained from DigitalGlobe (2016). However, the accuracy assessment between WV-3-derived SDB and CHARTS bathymetric lidar data indicated a slightly higher RMSE (1.112 m) than the L8 blue/green band ratio (1.065 m), although the overall mean error for WV-3 SDB was slightly lower (0.867 m) than the L8 blue/green ratio (0.947 m) (table 1). Several scientific publications have presented questions about the advantage of using atmospherically corrected imagery when attempting to describe the variability of optical water properties because the atmospheric corrections may pose unnecessary bias in accurately assessing the spatial models because of cumulative increase in error uncertainty (Goodman and others, 2008; Kutser, 2012; Monteys and others, 2015). Additionally, Harris Geospatial Solutions (2017) (developer of the ENVI software) recommends when using their relative water depth tool, which is based on Stumpf and others (2003), it is typically best to not perform atmospheric correction. Atmospheric correction of littoral or marine areas often alters the data such that calculating water depths may produce anomalous and unsatisfactory results (Harris Geospatial Solutions, 2017).

The ratio of natural logarithms approach depends on ancillary geospatial data, such as multibeam echo sounder or bathymetric lidar, to calibrate relative SDB profile estimates to absolute depths. For this research, the L8 and WV-3 imagery that was used to derive SDB was acquired in 2016. The CHARTS bathymetric lidar data that were used to calibrate relative SDB depths were acquired in 2006, a 10-year temporal span. Although single- and multibeam soundings were available from NGA for SDB calibration, some depths were collected as far back as 1944 (National Geospatial-Intelligence Agency Maritime Safety Office, 2011; 2017). Some of the older soundings may be viable for SDB calibration in more stable locations; however, the Majuro Atoll near-shore zone is an area of high wave energy and dynamics that make it prone to bathymetric change with time. Therefore, it was important to use the most recent and best available CHARTS bathymetric lidar data (Naval Oceanographic Office, 2006a; 2006b) for SDB calibration purposes in the Majuro Atoll, Republic of the Marshall Islands.

The lack of high-resolution coastal TBDEMs has been identified as a critical data gap required for flood, storm surge, hurricane, and sea-level rise inundation hazard zones for atoll nations (Helweg and others, 2014; Palaseanu-Lovejoy and others, 2017b). To fill this need, the CoNED Applications Project created an integrated 1-m TBDEM for the Majuro Atoll, Republic of the Marshall Islands, that consists of the best available multisource topographic and bathymetric elevation data for onshore and offshore areas (fig. 5) (Danielson and others, 2016; Palaseanu-Lovejoy and others, 2017b; Thatcher and others, 2016).

The Majuro Atoll TBDEM integrates nine different data sources:

- Structure from motion (SfM) (Palaseanu-Lovejoy and others, 2017b)
- Unmanned aircraft systems (UAS) imagery (more than 35,000 images collected—the largest SfM UAS collection in the western Pacific) (Palaseanu-Lovejoy and others, 2017a; 2017b)
- Real-time kinematic Global Navigation Satellite Survey survey points (Palaseanu-Lovejoy and others, 2017a; 2017b)
- USGS L8 imagery (U.S. Geological Survey, 2016b)
- DigitalGlobe WV-3 imagery (DigitalGlobe, 2016)
- SDB vertical profile estimates (Palaseanu-Lovejoy and others, 2017b; this publication)
- South Pacific Applied Geoscience Commission (SOPAC) bathymetry (Kruger and Kumar, 2008)
- Hydrographic surveys, single-beam acoustic surveys, and multibeam acoustic surveys obtained for SDB calibration purpose from NGA (National Geospatial-Intelligence Agency Maritime Safety Office, 2011; 2017)
- The U.S. Naval Oceanographic Office CHARTS bathymetric lidar data (2006a; 2006b).

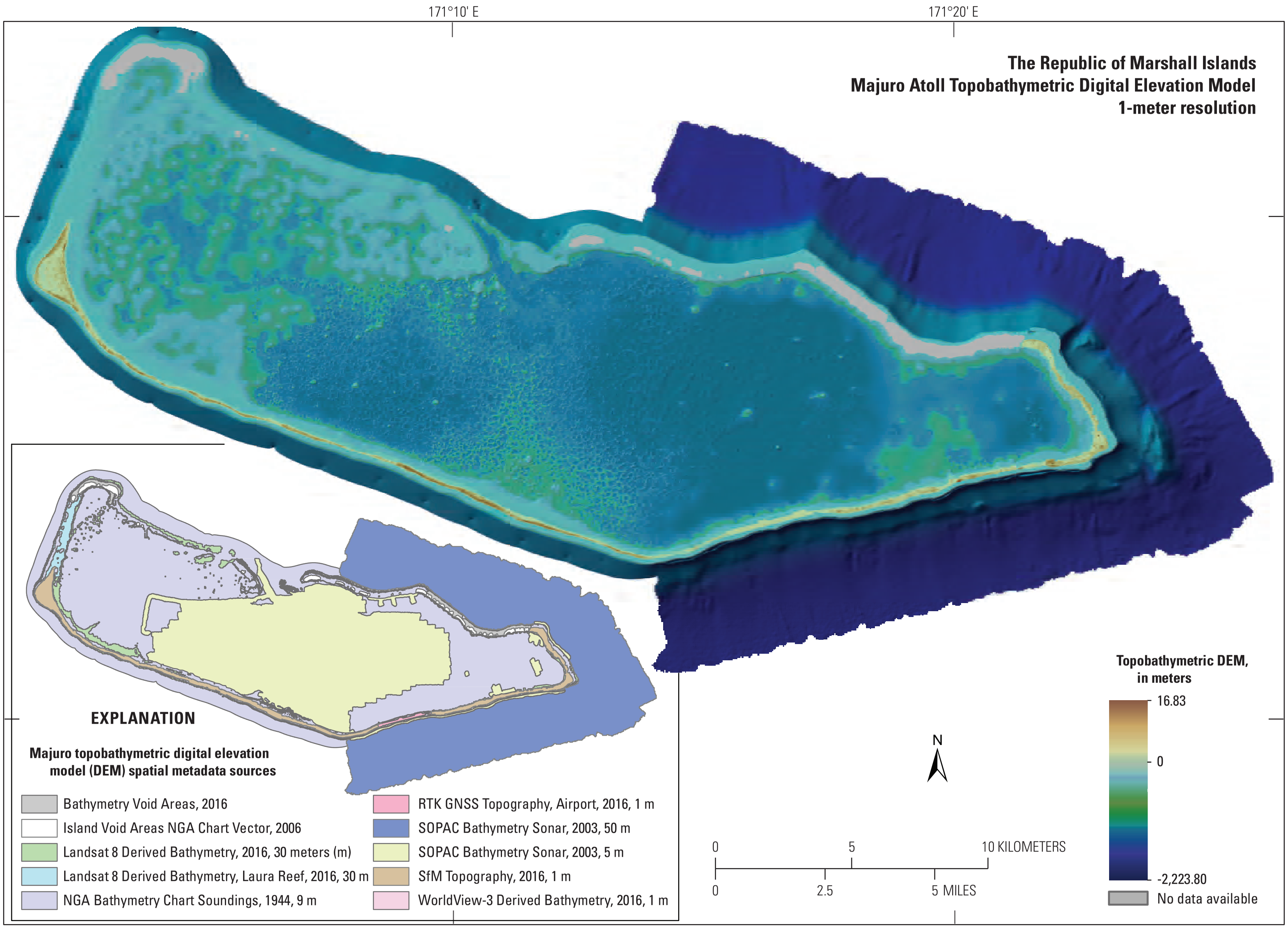

Figure 5. Satellite-derived bathymetry integrated into the Majuro Atoll, Republic of the Marshall Islands, topobathymetric digital elevation model (Palaseanu-Lovejoy and others, 2017b). Other spatial metadata sources include the National Geospatial-Intelligence Agency (NGA) bathymetry chart soundings, real time kinematic (RTK) global navigation satellite survey (GNSS) topography, South Pacific Applied Geoscience Commission (SOPAC) sonar, and Structure from Motion (SfM) topography.

Conclusion

Low-lying coral atolls, such as the Majuro Atoll, Republic of the Marshall Islands, are subject to natural hazards, such as flooding, exceptionally high tides, hurricanes, and sea-level rise. Considering that the highest natural elevation on the atoll is only 3 m above sea level, the lack of high-resolution topobathymetric data has been identified as a critical data gap for climate vulnerability and adaptation efforts and for high-resolution inundation modeling for atoll nations. Active sensors, such as light detection and ranging (lidar) or sound navigation and ranging (sonar), have been used to collect bathymetric data; however, green laser lidar acquisitions aboard a small fixed-wing aircraft are challenging because of the costs associated with mapping remote Pacific islands. Ships collecting soundings cannot operate safely while navigating close to the shore; therefore, remote sensing research that uses ocean optics to estimate near-shore bathymetry using passive multispectral satellite imagery, such as Landsat 8 (L8) or DigitalGlobe WorldView-3 (WV-3), has become a more cost-effective means for mapping near-shore bathymetry to assess vulnerability to natural hazards in low-lying atolls in the northern tropical Pacific. This study is one of the first attempts to use satellite-derived bathymetry (SDB) for shallow near-shore bathymetry in the context of a tropical carbonate platform.

The most common method for deriving SDB from passive satellite imagery is the band ratio-based technique, commonly called the natural logarithm approach, in the International Hydrographic Organization Intergovernmental Oceanographic Commission General Bathymetric Chart of the Oceans Cook Book. The purpose of the SDB research was to apply the band ratio technique to L8 at-sensor radiance imagery and WV-3 atmospherically corrected imagery to characterize the attenuation of light within the water column in the coastal waters surrounding the Majuro Atoll, Republic of the Marshall Islands. Attenuation coefficients were applied to relative vertical profile bathymetric estimates that were calibrated to Compact Hydrographic Airborne Rapid Total Survey (CHARTS) bathymetric lidar data collected by the U.S. Navy and received from the Naval Oceanographic Office.

The CHARTS bathymetric lidar data yielded a strong linear relation with water depths. The L8 SDB blue/green band ratio exhibited a water attenuation extinction depth of 6 m with an R^2=0.9324; estimates derived from the coastal/red band ratio had an R^2=0.9597. At the same extinction depth, SDB estimates derived from WV-3 imagery exhibited an R^2=0.9574. Accuracy assessments were completed for SDB using the CHARTS bathymetric lidar data, which indicated a positive bias of 0.947 m for the L8 blue/green band ratio, 0.285 m for the L8 coastal/red band ratio, and 0.867 m for the WV-3 derived bathymetry. It is unclear if the positive bias was because of the water conditions (waves, tide, or water clarity), errors introduced by the instrument or mode of deployment, atmospheric conditions, or off-nadir angle of the high-resolution imagery. Therefore, additional investigations were completed based on depth intervals for overall errors, 0–4 m errors, and 4–6 m errors (6-m extinction depth). The L8-derived bathymetry exhibited a bimodal distribution, whereas the WV-3 derived bathymetry was positively biased for both depth intervals.

Additional information regarding the CoNED Applications Project is available at the USGS Coastal Changes and Impacts website at https://topotools.cr.usgs.gov/ and the CoNED Applications Project website at https://topotools.cr.usgs.gov/coned/.

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