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Precision assessment of ICESat-2 ATL03 Photon Data for Coastal Bathymetry: Comparison with Airborne Lidar Measurements

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Abstract Summary

Advances in sensors and bathymetric acquisition methodologies are fundamental to monitoring aquatic environments, particularly in coastal regions that require high precision due to their ecological and strategic importance. This study evaluates the accuracy of the ATL03 by-product for coastal bathymetry using Fernando de Noronha as the test area because its clear waters allow for greater laser signal penetration. Integrating aerial and orbital platforms shows potential for overcoming the limitations of traditional methods. The ATLAS sensor, carried by NASA's ICESat-2 satellite, operates in the green range. From an altitude of around 500 km, it emits six laser beams and detects individual photons reflected off the Earth's surface or underwater. NASA has validated the ATL03 product by comparing it with terrestrial and aerial surveys. This demonstrates that the ATL03 product is versatile, not only for monitoring the cryosphere, but also for applications in oceanography, hydrology, and atmospheric sciences. This paper compares ICESat-2 data with airborne lidar surveys conducted by the Geological Survey of Brazil (SGB) in 2018 over the Fernando de Noronha archipelago. To ensure comparability and accuracy, the satellite data were processed with specific geophysical corrections, including geoidal, atmospheric, tidal, and refraction adjustments. The results showed strong correlations between ICESat-2 and the reference data, with R^2 values ranging from 0.93 to 0.99 and slopes close to 1. Despite deviations observed in all beams, generally indicating overestimation of height, average absolute errors remained between 2.1 and 3.0 meters and RMSE values between 2.3 and 4.5 meters. These results demonstrate that ATL03 data can provide reliable bathymetric estimates in optically clear and shallow coastal waters with appropriate corrections.

Introduction

The development of remote sensing technologies for acquiring bathymetric data has become essential to meet the growing demand for detailed cartography of aquatic environments. This is important in coastal areas, where intense economic activity, ecological sensitivity, and the effects of climate change require precise and scalable cartography solutions.

Several remote sensing techniques have been used for bathymetric and geomorphological surveys, each with its own advantages and disadvantages. The most prominent are satellite-derived bathymetry (SDB), airborne radar bathymetry (ALB), and the advanced topographic laser altimeter (ATLAS) system aboard ICESat-2. Launched in 2018, ICESat-2 operates at an altitude of approximately 500 km, using a green (532 nm) photon-counting laser capable of detecting the return of individual photons from surface and subsurface reflections. In clear water conditions, the ICESat-2 can penetrate depths of 40–60 meters and achieve point densities of nearly 10 points per square meter (Neumann et al., 2019; Markus et al., 2017). Although the ICESat-2 was originally designed for cryospheric studies, it has demonstrated growing potential in oceanographic and coastal applications. Its polar orbit with a 91-day revisit cycle allows for repeated and extensive coverage. The ATL03 subproduct provides photon geolocation data, associating return times with the position and orientation of the satellite. However, data quality can be affected by atmospheric and optical properties of water.

Fernando de Noronha was selected as a test site to evaluate the performance of this orbital sensor in shallow tropical marine environments due to its clear waters, which allow laser penetration and provide favorable conditions to evaluate bathymetric accuracy. The island's coastal features, including abrupt depth changes, coral reefs, rocks, and dynamic conditions such as waves, tides, and winds, present additional challenges for in situ surveys, making remote sensing approaches especially advantageous.

This article compares ICESat-2 ATL03 data with airborne lidar data collected by the Brazilian Geological Service (SGB) in 2018 over the Fernando de Noronha archipelago. The ATLAS satellite data were corrected for specific geophysical effects, including geoidal undulation, atmospheric delay, tidal level, and water refraction, to evaluate the methodological accuracy and applicability of ATL03 for coastal and oceanic bathymetry in clear water environments.

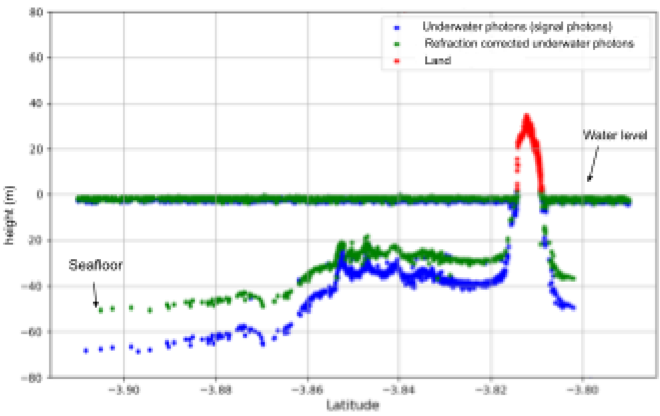
Method and Theory

The ICESat-2 mission transformed spaceborne altimetry by employing the Advanced Topographic Laser Altimeter System (ATLAS), which utilizes single-photon counting technology. ATLAS emits six green laser beams (532 nm) arranged in three cross-track pairs. Each pair of beams pulses at 10 kHz, producing six ground tracks labeled gt1l, gt1r, gt2l, gt2r, gt3l, and gt3r (Neumann et al., 2019). The instrument measures surface elevation by detecting photons reflected from the Earth's surface or water, achieving a vertical precision of up to 3 cm and a spatial resolution of approximately 10 points per m². The footprints have a diameter of ~17 m and are spaced ~71.2 cm apart along-track (Markus et al., 2017). ATL03 classifies photons into five surface types—land, ocean, terrestrial ice, sea ice, and inland water—using geophysical masks (Neumann et al., 2019).

To ensure accurate bathymetric retrievals, geophysical corrections are applied: Solid Earth Tides and Ocean Loading; Ocean Dynamic Topography; Geoid Correction and Refraction correction. Together, these corrections improve the accuracy of ICESat-2 bathymetric measurements, enabling reliable topographic and underwater terrain mapping. To ensure consistency and reliability in the comparison with airborne LiDAR data, photon selection was restricted to those associated with the seafloor and classified with confidence levels 0, 1, 2, 3 and 4. This selection process involved identifying and separating surface photons from subsurface ones using elevation histograms, followed by clustering of valid seafloor returns. The inclusion of level 0 photons was particularly important in deeper or low-reflectance areas, where attenuation often limits the detection of higher-confidence photons.

Results

Photon signals from the seabed were successfully detected from the ICESat-2 ATL03 raw dataset. In the study area, all six ICESat-2 beams passed over the region on 2021/07/21.



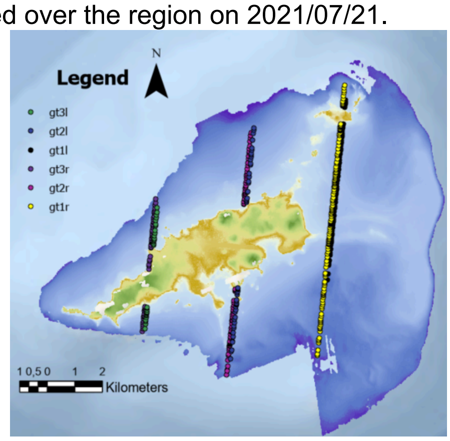


Figure 1. Photon elevations for the gt1r beam were acquired on July 21, 2021, at 05:26:42 UTC, after applying key geophysical corrections: refraction, geoid adjustment, ocean dynamic topography, solid Earth tides, and ocean loading. In the figure, dots near zero represent surface photon returns; red dots represent above water features, blue dots correspond to underwater photons before refraction correction; and green dots indicate seafloor photon positions after the refraction. The map of Fernando de Noronha with tracks of all the beams is on the right.

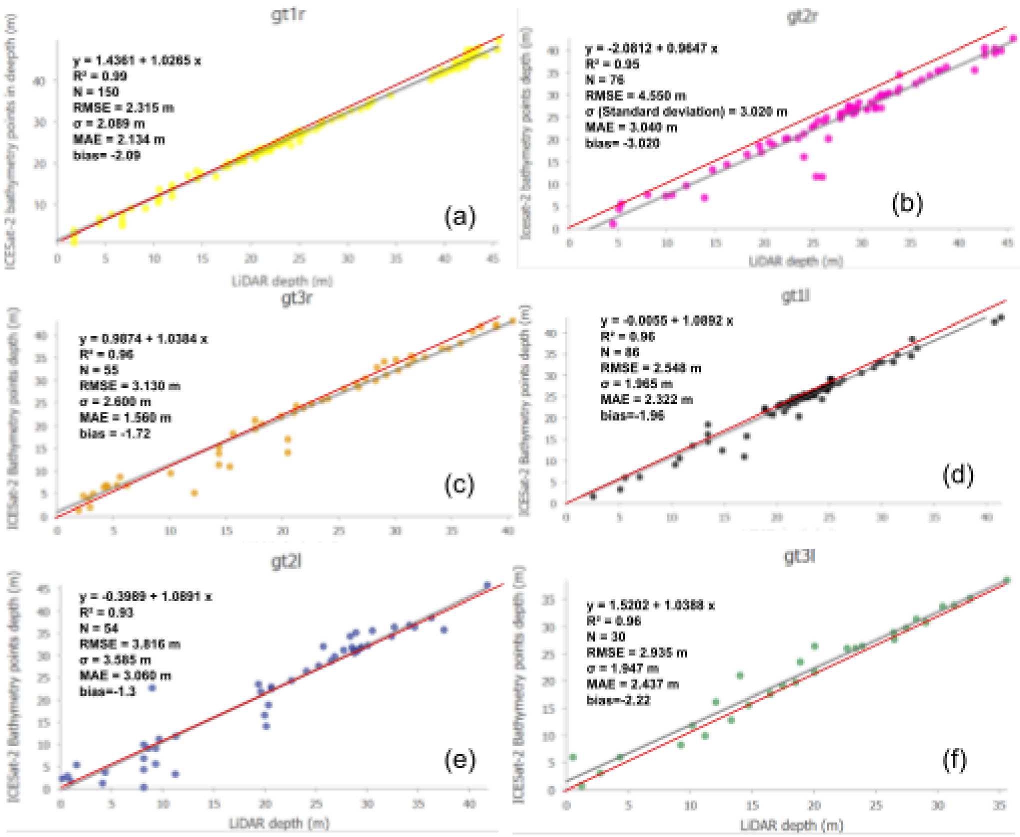


Figure 2: Comparison between the corrected ICESat-2 bathymetric elevations (Y-axis) and reference airborne LiDAR bathymetry (X-axis) acquired over Fernando de Noronha Island. The black line represents the computed linear regression and the red line represents the ideal y=x function.

The error analysis between the depths measured by ICESat-2 and the reference data from airborne LiDAR reveals a variable performance among the different beams, with RMSE values ranging approximately from 2.3 m to 4.5 m. This range indicates that, on average, the differences between the measurements and the references fall within these values, demonstrating moderate sensor accuracy for applications in coastal environments. The closeness between the RMSE and MAE values suggests a balanced error distribution, without a predominance of extreme outliers.Furthermore, the standard deviation (σ) of the errors indicates that the variability among the measurements is relatively low for most beams, reflecting good consistency in the obtained results. However, some beams show greater dispersion, which may be related to local acquisition conditions or specific sensor characteristics.

The systematic presence of a negative bias across all beams indicates a tendency of ICESat-2 to overestimate depths, to record deeper values (more negative) compared to airborne LiDAR. This systematic overestimation represents a systematic error that should be taken into account in analyses and, when possible, compensated for in practical applications to ensure greater reliability of the results. More specifically, the regression analysis of the six beams reveals strong linear correlations between ICESat-2 and LiDAR depths, with coefficients of determination (R^2) ranging from 0.93 to 0.99. The beam gt1r exhibits the highest correlation (R^2 = 0.99) and the lowest RMSE (2.32 m), showing a slight underestimation indicated by a negative bias of -2.1 m, despite the regression slope being close to 1 (b ≈ 1.02), which suggests a generally good linear trend with possible overestimation at higher depths.

The gt2r beam shows moderate underestimation with a larger RMSE (4.5 m) and a slope less than 1 (a = -2.1), indicating greater error dispersion and an underestimation tendency, especially at higher depth values. The gt3r beam presents a slope above 1 (b = 1.04), indicating increasing overestimation as depth increases, though the negative bias (-1.72 m) points to a moderate overall underestimation. Similarly, the beams on the left side (gt1l, gt2l, and gt3l) show good correlation and comparable RMSE values, with slopes greater than 1, suggesting overestimation tendencies at greater depths. However, all these beams maintain a negative bias, indicating moderate underestimation across the board.

In summary, the combined analysis of regression parameters and error metrics provides a comprehensive understanding of ICESat-2's bathymetric mapping performance. It highlights both its potential applicability and limitations for detailed surveys in complex coastal areas such as the Fernando de Noronha Archipelago, where accurate depth estimation is critical for environmental monitoring and resource management.

Conclusions

This study evaluated the potential of ICESat-2 ATL03 for shallow water bathymetric applications in the Fernando de Noronha Archipelago, using airborne LiDAR data as a reference from a single pass for methodological assessment. Linear regressions between the corrected ICESat-2 depths and the reference data showed strong correlations across all beams, with R^2 values ranging from 0.93 to 0.99. Regression slopes were generally close to or slightly above 1, indicating that ICESat-2 captures depth variations with good consistency. A systematic negative bias was observed in all beams, indicating that ICESat-2 tends to overestimate depths (i.e., report deeper values) as the measured depth increases, while it underestimates depths closer to the waterline, likely due to reverberation effects present in the data. This bias may also be related to differences in spatial resolution, waveform processing limitations, local topographic variability not fully captured by the satellite sensor, and incomplete filtering of outliers. Among the beams analyzed, GT1R and GT3R showed the best overall performance, combining low bias, low error dispersion, and strong correlation, suggesting their particular suitability for bathymetric mapping in similar shallow water environments. Despite some variability between beams, the results confirm that ICESat-2 provides viable bathymetric data when supported by appropriate corrections and validation against high-resolution reference measurements. The sensor's consistent performance across multiple beams reinforces its potential for regional-scale coastal assessments, especially where conventional hydrographic methods face limitations.

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