

ABSTRACT

Spaceborne laser altimetry has emerged as a powerful tool for acquiring high-resolution 3D topographic data for Earth observation, with applications ranging from developing global control point libraries to monitoring glacier dynamics and water levels and estimating forest biomass. Two prominent missions, ICESat-2 (Ice, Cloud, and land Elevation Satellite-2) and GEDI (Global Ecosystem Dynamics Investigation), have set new standards in data quality and coverage for global Earth observation. ICESat-2's Advanced Topographic Laser Altimeter System (ATLAS) generates numerous valuable datasets. The ATL03 dataset provides photon-level elevation and geolocation information, while ATL08 delivers terrain height across fixed segments. By analyzing regions with diverse topography, this study comprehensively evaluated the quality of ATL08 data against the 3D Elevation Program (3DEP) Digital Elevation Model (DEM). Our analysis identified performance challenges of ATLAS in daytime data collection, especially in mountainous areas with dense canopy cover. To address these limitations, we developed a gravity density based anisotropic filtering method that jointly uses the ATLAS strong and weak beams to robustly detect signal and ground photons from ATL03 data. Compared to existing ATL03 and ATL08 products, our method demonstrated superior consistency with 3DEP DEM, especially for strong beam data collected during daytime in high-relief, densely vegetated areas. The large sparsity of space lidar coverage constrains global DEM generation at high resolution. To overcome this limitation, we introduced two novel methods and evaluated them with regions of four entire US counties. Through a holistic mathematical framework, the first method combines ICESat-2 and GEDI elevation data with existing global DEMs, leading to improved DEM products and enhanced accuracy of GEDI measurements. The second method employs a Transformer-based Generative Model for Spatial Interpolation (T-GMSI) based on the vision transformer (ViT) architecture. Experimental results demonstrated that T-GMSI is both effective and transferable in handling the sparsity limitation and can produce accurate DEMs from ICESat-2 and GEDI measurements in previously unseen regions. This study advances global terrain modeling by addressing space lidar limitations in data quality and spatial coverage through meticulous analysis and sophisticated analytics. The proposed methods significantly improve the accuracy and scalability of DEM generation, providing adaptable solutions for generating precise DEMs across diverse regions and offering valuable tools for scientists, engineers, and policymakers.