Passive ground-based optical techniques for monitoring the on-orbit ICESat-2 altimeter geolocation and footprint diameter

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Key Points:

- Corner cube retro-reflectors are passive optical components that provide a distinct and recognizable reflection signature to space-based lidar for validation of the measurement geolocation.
- The passive optics also provide a methodology for determining the diameter of the laser footprint on the surface and the effects of the atmospheric attenuation on the effective footprint diameter.
- Validation studies confirm that the accuracy ICESat-2 geolocation at both mid-latitude and polar regions currently meet the mission requirement for position quality.
Plain Language Summary

NASA launched its second Earth observing laser altimeter in 2018 with mission objectives of studying the changes in our climate by monitoring global elevations, particularly in the polar regions. Since the mission is focused on generating accurate elevations and elevation change assessments, the geolocation accuracy of the measurements is of upmost importance to each of the scientific disciplines supported by these observations. Geolocation validation is required to ensure that the mission is meeting its science objectives. One validation technique uses small optical reflectors that provide a unique signal back to the satellite. These signal locations within the ICESat-2 data can be compared to the surveyed positions of the optics to determine the data quality. Results from this technique indicate that the measurements are accurate to within 3.5 m, with a standard deviation of 2.1 m. In addition, the optics can be used to determine the effective laser footprint diameter on the surface when multiple optics are illuminated during a single satellite overpass. For those qualifying overpasses, the diameter is estimated to have an average value of 10.9 m with a standard deviation of 1.2 m. The variation in diameter is thought to be a result of environmental influences on the laser-energy-level at the surface, most likely linked to atmospheric conditions.
Abstract

Corner cube retro-reflectors (CCRs), passive optical components, are used to independently evaluate the geolocation accuracy and effective laser footprint diameter of NASA’s laser altimetry mission, ICESat-2, at two specific study sites: White Sands Missile Range in New Mexico and along a segment of the 88° S line of latitude in Antarctica. The CCR methodology provides ICESat-2 the ability to monitor these altimeter performance metrics throughout the mission lifetime as an indicator of the health of the instrument and the quality of the observations for science applications. The results using this technique reveal a mean geolocation accuracy of the ICESat-2 measurements of 3.5 m ± 2.1 m, meeting the mission requirement of 6.5 m. For those instances where multiple CCRs are illuminated, the mean effective laser footprint diameter is 10.9 m ± 1.2 m, with the variability assumed to be due to the influence of atmospheric conditions, but warrants further investigation.

1. Introduction

The Ice, Cloud and land Elevation Satellite-2 (ICESat-2) is a NASA Earth observing satellite on-orbit since September 2018. The mission is NASA’s response to the need for repeated elevation measurements over the polar regions to quantify ice-sheet elevation change and sea ice characterization. ATLAS (Advanced Topographic Laser Altimeter System) is the on-board instrument, a photon-counting lidar designed to provide precise ranging measurements using individual 532-nm photons reflected from the surface of the Earth. These ranging measurements, combined with the satellite observatory position and laser pointing determination, enable the determination of centimeter-scale elevation change over seasonal and annual cycles (Neumann et al., 2019a, Smith et al., 2020). ATLAS has a single laser, 10 kHz repetition rate, and uses a diffractive optical element to divide a single laser pulse into 6 individual laser footprints. The beams are configured into 3 beam pairs spaced by ~3.3 km across track (Markus et al., 2017). Within each pair, the beams are separated by 2.5 km along-track and 90 m across-track. Each beam pair is composed of one strong beam and one weak beam, with the strong beam having ~4x the energy of the adjacent weak beam. The relative locations of the weak and strong beams in the footprint pattern is dependent on the orientation of the observatory relative to the direction of flight.
The mission requirements on satellite position and pointing determination ensure that the observations accurately support the mission science objectives. Precision orbit determination (POD) is required to be within 5-cm radial accuracy while the precision pointing determination (PPD) requires laser pointing knowledge to within 3.7 $\mu$rad (0.8 arc sec) precision, resulting in a total measurement geolocation knowledge requirement of 6.5 m one sigma, or ~2.7 arc sec. The PPD quality is dependent on the ability to resolve the influence of thermal variations and spacecraft orientation on the pointing efficacy (Luthcke et al., 2021, Bae et al., 2021, Magruder et al., 2021). On-orbit biases (static and dynamic) for instrument pointing, ranging, and timing are determined using a regular sequence of maneuvers over the ocean (‘ocean scans’) and within a full orbit (‘around the world scans’) to recover the range residuals that inform the geolocation corrections (Luthcke et al., 2021, Thomas et al., 2021, Luthcke, et al., 2005). Although the methodology of assessing the on-orbit errors with dedicated satellite maneuvers is well established, independent assessments of geolocation at specific locations validate the results and provide the opportunity to evaluate the data quality at varying length scales. Many of the independent methods involve direct comparison between ICESat-2 elevations and ground reference surfaces created from airborne lidar (Magruder et al., 2020) or ground-based GPS surveys (Brunt et al., 2021, Brunt et al., 2019). These comparative techniques can determine both the vertical and horizontal accuracy of the geodetic position of the observation at the photon level or aggregated along-track segments.

A unique, independent method for geolocation accuracy assessment relies on small corner cube retroreflectors (CCRs). CCRs are passive optical components designed to reflect light along the angle of incidence with diffraction properties dependent on the CCR diameter and wavelength (Sun et al., 2019). The CCR size selection relative to space-based laser characteristics creates the opportunity to provide distinct, observable reflections despite the significant ranging distances (Magruder et al., 2020). Comparing the satellite measurement geolocation to the known geodetic surveyed position of the CCR determines the horizontal positional accuracy. This technique was previously successful for ICESat (2003-2009; Magruder et al., 2005), MABEL (Multi Altimeter Beam Experimental Lidar) (Magruder and Brunt, 2018), and early ICESat-2 data (Magruder et al., 2020).

Here we present an evaluation of the ICESat-2 positional accuracy and the estimation of the effective footprint diameter using the aggregate of opportunities from October 2018 to May 2020.
as a follow-on study to the previous CCR method proof of concept (Magruder et al., 2020). Further, this study provides the initial exploration into possible atmospheric contributions to variations between independent assessments.

2. Data and Methods

Validation using CCRs requires arrays positioned strategically near the ICESat-2 reference ground tracks (RGTs) to create multiple opportunities for CCR data collection during the orbital repeat cycle. This analysis uses two field locations of clusters of CCR arrays: White Sands Missile Range (WSMR) and along the 88° S (88S) line of latitude. The size, geometry and composition of the arrays are designed to accommodate the pointing control accuracy of the satellite and the beam configuration and depend on ±45 m pointing control (Magruder et al., 2021). Unique heights of the CCRs within each array ensure that any illuminated CCR is uniquely identified once the CCR return signatures are separated from the surface-return signatures.

The arrays at WSMR utilize 8 mm diameter CCRs on poles with height variations from 0.6 m to 3.0 m (Magruder et al., 2020). The configuration of the arrays at WSMR is a diamond pattern, which was designed with specific ICESat-2 tracks in mind, but the mission has also targeted this array by pointing ATLAS at specific points within the arrays.

The arrays along 88S utilize a mixture of 6- and 8-mm diameter CCRs. They were originally placed in January 2018, during a GNSS ground survey (Brunt et al., 2021, Brunt et al., 2019), with the positions of the CCRs resurveyed during two subsequent surveys (January 2019 and January 2020). The 88S arrays are generally linear sets of CCRs. This less complex array geometry is due to the convergence of ground tracks in proximity to the arrays at the southern limit of the ICESat-2 orbit.

The CCR analysis focuses solely on the ICESat-2 Global Geolocated Photons (ATL03) along-track data product (Neumann et al., 2019a). All ATL03 data used is Release 003, which are available at the National Snow and Ice Data Center (NSIDC; Neumann et al, 2019b). ATL03 contains both surface signal and ambient solar background photons but provides signal confidence labels to delineate between these two classifications. This is an important step, particularly for the majority of the higher-level data products (Level 3a) that rely on those photons with a high surface-signal probability to interpret the surface elevation (Smith et al., 2018, Kwok et al., 2020, Neuenschwander et al., 2020).
The ICESat-2 orbit provides 7 opportunities (~twice per month) for CCR data collection over the WSMR location given the 5° off-nadir pointing capability of the observatory. Each instance offers variability in satellite direction of flight (ascending or descending pass) and observatory orientation (forward or backward facing, relative to the direction of flight). Given this variability, this study provides a method for understanding the efficacy of the pointing calibration, the pointing control, the effective footprint diameter, and the overall geolocation knowledge of the satellite-based measurements under conditions specific to a mid-latitude and polar orbital positions.

The analysis of the CCR signatures is described in Magruder et al. (2020) and details the approach to distinguishing CCR signatures from those associated with surface-signal returns. Once the CCR returns are identified and extracted, the analysis generates a statistical estimate of the along-track CCR signal length (along-track distance) using the expected Gaussian energy distribution of the laser footprint. That is, the signal along-track distance is estimated relative to the Gaussian distribution of return photons. The laser footprint diameter retrieval is representative of a Gaussian beam diameter, defined as the 2-sigma value of the signal distribution curve associated with 86% of the total beam energy based on pre-launch measurements of a Gaussian energy pattern (Martino et al., 2019). For a strong beam, the Gaussian beam energy value is 120 μJ while a weak beam provides 30 μJ (Neumann et al., 2019a). The key parameter in the determination of both the geolocation validation and the effective footprint diameter is this determination of the along-track distance between the initial and final illuminating laser footprints on the CCR, which is ultimately the chord length of the CCR signal returns. The chord length is critical to understanding where the CCR is located relative to the center of the laser footprint.

The determination of the CCR return signal chord length is complex. The geolocation of all detected photons for each laser shot are assigned to the laser footprint centroid (Luthcke et al., 2019). Thus, the precise location of the reflected surface within a laser footprint is unresolvable at that length scale and all photons received per shot will be quantized to the estimated ‘ground bounce point’ of the laser footprint centroid. Once the CCR signature length is extracted, the statistical center of the chord can determine the ATL03 geolocation for comparison to the known position of the CCR as well as the distance from the laser footprint centerline. This is more of an estimation when only one CCR is illuminated since that scenario lacks a geometric constraint.
created when multiple CCR hits that ultimately provide a deterministic assessment of both the geolocation and the effective footprint diameter by collectively fitting the signal signatures with known positions of the contributing CCRs. The solution is determined through an iterative process of fitting the CCR signal returns for a given beam diameter. By minimizing the horizontal residuals of the combined comparison over the sequence of CCR illuminations a quantitative assessment is achieved for the offsets in the northing and easting directions that inform the accuracy of the horizontal position of the measurements. Additional details of the method are provided in Magruder et al. (2020).

Confidence in the determination of geolocation accuracy and effective footprint diameter is dependent on the signal level. The number of signal photons (signal reflection strength) is dependent on both the incident energy at the surface and returned energy level received. The signal reflection strength is primarily dependent on the surface reflectance, but atmospheric attenuation is also a significant contributor. Clouds, aerosols, and water vapor in the atmospheric column attenuate the laser light through absorption and scattering. Initial predictions based on data prior to the launch of ICESat-2 suggested that column optical depth, a measure of the observed attenuation related to clouds and aerosols, could attenuate > 50% of the laser energy if the optical depth is above 1.0 (Palm et al., 2020).

To assess the atmospheric effects on the CCR results for geolocation validation and footprint diameter retrievals, parameters from the ICESat-2 atmospheric data product (ATL09) are used. These parameters include calibrated attenuated backscatter (CAB), relative humidity, temperature, and pressure (Palm et al., 2020). Specific humidity is determined from these variables following the computation of vapor pressure through the standard equations provided in Rogers & Yau (1996). These atmospheric profiles are separated into estimated boundary layer (0 – 1 km), low (1 km – 5 km), moderate (5 – 10 km), and high altitudes (10 – 15 km) to pinpoint specific levels where the moisture content is potentially high or where temperature inversions may trap scattering particles. For the cases at WSMR, the calculated optical depth and profile data are used to investigate the possible correlation of these values to variations in either the observed effective footprint diameter or geolocation accuracy as an initial understanding. For the cases at 88S, other parameters are considered from ATL09, including the blowing snow confidence level (Palm et al., 2020), which could cause additional attenuation through signal scattering. The impact of the atmosphere will vary between the two locations based on differing
atmospheric characteristics. Attenuation via moisture effects are more likely at WSMR because
temperatures are higher allowing the air to hold more water vapor. Calculation of the total
column optical depth remains in development for a future release of the ICESat-2 atmospheric
data products. We also note that the top of the troposphere, where noticeable stratospheric
warming begins, is at ~8 km at 88S, but extends above ~12 km at WSMR.

3. On-orbit assessment 2019-2020

An early CCR opportunity (March 2019) at WSMR illuminated 3 CCRs with the center pair
weak beam. This first analysis provided an ATL03 geolocation accuracy assessment for the first
time and helped establish the deterministic method for recovery of the effective footprint
diameter (Magruder et al., 2020). The effective footprint diameter result for this case was 10.6 m
and the ATL03 horizontal geolocation was accurate to within 2 m. This was an important
analysis for several reasons as was the opportunity to automated the diameter determination and
enhance the understanding of how the spacecraft pointing control is executed to inform future
pointing requests (i.e., the uploading of commands to the satellite to maneuver and target a
specific location). A successful WSMR overpass in September 2019 also illuminated 3 CCRs
with the center strong beam, providing the second opportunity to explore the validation
technique. The analysis of these signatures indicated an effective footprint diameter of 12 m and
horizontal geolocation offset of 5 m. Magruder et al. (2020) examined the effective footprint
diameter recovered between the weak (March 2019) and the strong (September 2019) beams and
attributed the disparity to atmosphere attenuation and potential loss of return signal at the edges
of the footprint where the energy is lower. Given the two instances of CCR signal retrievals, the
concept and implementation were confirmed but the small sample size of the successful
illumination of CCRs did not warrant statistically relevant conclusions for geolocation accuracy
and beam diameter.

Results presented here build on the initial results of Magruder et al. (2020). Since September
2019, attempts have been made to point ATLAS at WSMR for every overpass opportunity. Some
satellite overpasses were unsuccessful because they did not hit the CCR arrays while others were
unsuccessful because they occurred during cloud cover that prevented returns from either the
surface or the CCR. Other failed opportunities were associated with satellite operational events
that either superseded the CCR pointing requests or suspended on-orbit data collection
temporarily.
A successful satellite overpass example is presented in Figure 1. RGT #28, a descending pass on 28 March 2020, illuminated 5 CCRs in both the north and east WSMR arrays after the satellite performed a roll maneuver to point ~4° off-nadir. Figure 1(a – b) provides the configuration of the satellite ground track (ATL03 geolocated photons) and the array locations. In Figure 1 the signal photons attributed to the CCR returns are blue and the remaining ATL03 signal photons are green. Figure 1(d – f) presents the along-track heights for three different CCRs. The heights of the photon returns allow identification of a specific CCR based on the known array pattern. In this case of Figure 1(d – f), the sequential heights of 3.0, 0.75 and 3.0 m, from north to south, is indicative of a pattern containing CCR04, CCR08 and CCR12 (the east array analysis is done similarly). Using the method described in section 2 gives a 12.0 m effective footprint diameter and a horizontal geolocation offset of 4.3 m (RMSE 2.1 m). The RMSE is representative of the goodness of fit between the ATL03 geolocation to the 5 individual CCR positions. Figure 1(c) illustrates the adjustment of the original track (black line) to accommodate the geometry of the known CCR locations (red X’s) and the signal chord lengths (blue circles). The translation between the known CCR surveyed locations (red X’s in Figure 1c) and the predicted CCR locations (blue boxes in Figure 1c) is the estimate of the ATL03 geolocation accuracy.
Figure 1. 28 March 2020 WSMR overpass analysis of 5 individual CCRs; 3 of the illuminated CCRs were in the north array and 2 were in the east. Panels (a) and (b) show the ATL03 signal in green and the ATL03 CCR signal in blue. Panel (c) shows the estimated chord lengths (blue) and the solution (green) for determination of the effective footprint diameter and geolocation offsets that correspond to the geometry of the known locations of the illuminated optical components. Panels (d – f) provide the returns from CCR04, 08 and 12 in the north array indicating the height relative to the surface.
<table>
<thead>
<tr>
<th>WSMR overpass date</th>
<th>Beam Ground-track/RGT</th>
<th>Beam strength</th>
<th>Off-nadir angle (deg)</th>
<th>Slant range (m)</th>
<th>ATLAS spot number</th>
<th>Local time of collection</th>
<th>Horizontal geolocation error (m)</th>
<th>Effective footprint diameter (m)</th>
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<tbody>
<tr>
<td>3/31/2019</td>
<td>GT2R/28</td>
<td>Weak</td>
<td>2.46</td>
<td>485162</td>
<td>4</td>
<td>08:37</td>
<td>2.5</td>
<td>10.6</td>
</tr>
<tr>
<td>5/31/2019</td>
<td>GT2R/973</td>
<td>Weak</td>
<td>0.37</td>
<td>484743</td>
<td>4</td>
<td>17:04</td>
<td>3.0</td>
<td>8.5</td>
</tr>
<tr>
<td>9/28/2019</td>
<td>GT2R/28</td>
<td>Strong</td>
<td>2.52</td>
<td>485037</td>
<td>3</td>
<td>11:56</td>
<td>5.0</td>
<td>12.0</td>
</tr>
<tr>
<td>10/12/2019</td>
<td>GT2R/234</td>
<td>Strong</td>
<td>4.87</td>
<td>486609</td>
<td>3</td>
<td>23:15</td>
<td>3.8</td>
<td>10.6</td>
</tr>
<tr>
<td>10/31/2019</td>
<td>GT2R/531</td>
<td>Strong</td>
<td>3.27</td>
<td>484847</td>
<td>3</td>
<td>10:24</td>
<td>2.8</td>
<td>11.4</td>
</tr>
<tr>
<td>1/07/2020</td>
<td>GT1R/173</td>
<td>Strong</td>
<td>3.22</td>
<td>485483</td>
<td>5</td>
<td>18:03</td>
<td>0.7</td>
<td>8.3</td>
</tr>
<tr>
<td>2/08/2020</td>
<td>GT3R/676</td>
<td>Strong</td>
<td>1.67</td>
<td>484471</td>
<td>1</td>
<td>16:31</td>
<td>7.7</td>
<td>11.6</td>
</tr>
<tr>
<td>3/28/2020</td>
<td>GT3R/28</td>
<td>Strong</td>
<td>4.06</td>
<td>485998</td>
<td>1</td>
<td>03:16</td>
<td>4.3</td>
<td>12.0</td>
</tr>
<tr>
<td>5/09/2020</td>
<td>GT3R/676</td>
<td>Strong</td>
<td>1.72</td>
<td>484482</td>
<td>1</td>
<td>13:11</td>
<td>2.1</td>
<td>10.0</td>
</tr>
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Mean WSMR geolocation error and beam diameter

<table>
<thead>
<tr>
<th>88S overpass date</th>
<th>Beam Ground-track/RGT</th>
<th>Beam strength</th>
<th>Off-nadir angle (deg)</th>
<th>Slant range (m)</th>
<th>ATLAS spot number</th>
<th>Local time of collection</th>
<th>Horizontal geolocation error (m)</th>
<th>Effective footprint diameter (m)</th>
</tr>
</thead>
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<tr>
<td>12/10/2018</td>
<td>GT2R/1111</td>
<td>Strong</td>
<td>-</td>
<td>511475</td>
<td>3</td>
<td>21:49</td>
<td>0.4</td>
<td>11.6</td>
</tr>
<tr>
<td>1/18/2019</td>
<td>GT3L/318</td>
<td>Strong</td>
<td>-</td>
<td>511930</td>
<td>5</td>
<td>19:17</td>
<td>2.4</td>
<td>9.8</td>
</tr>
<tr>
<td>11/27/2019</td>
<td>GT3L/943</td>
<td>Weak</td>
<td>2.78</td>
<td>512538</td>
<td>2</td>
<td>04:27</td>
<td>3.3</td>
<td>11.1</td>
</tr>
<tr>
<td>12/30/2019</td>
<td>GT3R/59</td>
<td>Strong</td>
<td>2.81</td>
<td>512031</td>
<td>1</td>
<td>02:55</td>
<td>2.0</td>
<td>12.4</td>
</tr>
<tr>
<td>1/13/2020</td>
<td>GT2R/274</td>
<td>Strong</td>
<td>0.67</td>
<td>511625</td>
<td>3</td>
<td>04:47</td>
<td>8.5</td>
<td>11.5</td>
</tr>
<tr>
<td>1/24/2020</td>
<td>GT3R/438</td>
<td>Strong</td>
<td>2.81</td>
<td>512554</td>
<td>1</td>
<td>22:31</td>
<td>3.8</td>
<td>11.5</td>
</tr>
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</table>

Mean 88S geolocation error and beam diameter

Table 1. Results for geolocation and effective footprint diameter determination from white Sands Missile Range and 88S. ‘ATLAS spot number’ is a unique method of referring to the ATLAS beams, independent of the orientation of the observatory relative to the direction of flight.
4. Discussion

The CCR on-orbit results from Table 1 indicate that ICESat-2 is meeting the requirements for geolocation accuracy in the Release 003 data considered here and the pointing control capability. Table 1 provides the results of each relevant case at WSMR and 88S with the 1σ uncertainties included. Aggregation of the results give a mean effective footprint diameter of 10.9 m with a standard deviation of 1.2 m and a median value of 11.4 m. The overall horizontal geolocation error is 3.5 m ±2.1 m. Results specific to WSMR indicate the diameter retrievals are consistent over the 9 cases within a range of 8.3 m to 12 m (mean value 10.6 m ±1.3 m). Results for the 6 overpass cases at 88S indicate a mean diameter of 11.3 m ±0.8 m. The pre-launch measurements of the ATLAS laser beam divergence were 21.4 µrad and 19.7 µrad for the semi-major and semi-minor axes, respectively (A. Martino, pers. comm.). Using these pre-launch measurements and the ICESat-2 altitude range (486 km – 512 km) yields 9.5 m/10.4 m – 10.0 m/10.9 m for semi-minor/semit-major footprint axes on the surface. This is consistent with the CCR technique results.

To understand the variability in the observed effective footprint diameters we evaluated atmospheric and operational parameters that might influence the footprint characteristics and signal levels at the surface. Figure 2 provides a summary of the effective footprint diameter retrieval values and the parameters investigated.

4.1 Satellite Altitude

The satellite altitude has a dependence on latitude. Although the ICESat-2 overpass altitudes at WSMR for each overpass are ~484 km (Figure 2d), the slant range associated with the off-nadir pointing angle (Table 1) creates a longer divergence path length. However, the largest off pointing angle theoretically increases the footprint diameter by only 5 cm relative to nadir. The average altitude at 88S is nearly 30 km higher than at WSMR, which would imply that the footprint diameter on the surface would be larger by ~1 m if solely based on path length. The 0.7 m mean diameter difference between the altitudes of the two sites is consistent with this expected variation but does not account the potential impact of diameter retrieval relative to along-track alignment with the semi-major or semi-minor axes. The lower variability in effective footprint diameters at 88S in comparison to that at WSMR could be attributed to the consistency of the collection parameters (altitude and path length) or the lower susceptibility to atmospheric
influence based on the reduced vertical height of the boundary layers and the low water vapor content in this region.

4.2 Atmospheric Parameters

The atmospheric parameters examined are based on the GEOS-FPIT model results used to calculate the wet and dry tropospheric correction to ATL03 photon heights (Palm et al., 2019). Figure 2(a – c) shows column-property comparisons for two specific cases at WSMR, while Figure 2(e – f) make column-property comparisons between all the passes at both WSMR and 88S.

Humidity. The relative humidity (RH) and specific humidity (SH) profiles for WSMR in Figures 2(a – b) indicate large amounts of moisture in the lower atmosphere for the 31 May 2019 case (8.5 m effective footprint diameter), where SH is > 2 times larger than for the 28 March 2020 case (12.0 m effective footprint diameter) at 4 km above the surface. Overall, at WSMR, the decrease in effective footprint diameter with increasing SH confirms that moisture content is limiting signal returns. Figure 2(f) shows the effective footprint diameters (WSMR and 88S) with respect to the total SH and RH. RH and SH are used here to indicate the amount of water vapor present in the lowest portion of the atmosphere. Figure 2(f) also indicates that RH is high throughout the column. However, these results are misleading due to the cold temperatures at 88S, which are < -23 °C near the surface for all cases. The average temperature at WSMR near the surface was 13.4 °C. The 88S specific humidity is an order of magnitude lower than WSMR because of this 36 °C difference. Overall, SH for the cases at 88S are nearly the same across each instance to indicate that moisture is not influencing signal attenuation at this location.

Optical Depth. The column optical depth comparison for the 31 May 2019 and 28 March 2020 results at WSMR in Figure 2(c) indicates a possible correlation between increasing optical depth and smaller effective footprint diameters due to increasing attenuation as these results represent the current minimum (May 2019) and maximum (March 2020) diameter values for comparison. The column optical depth was analyzed to determine the presence of cloud and aerosol layers as the most probable parameter for indicating signal attenuation. However, the ATL09 CAB and related parameters capture only limited information on the state of the atmosphere at a given location. Clouds above the 12 km threshold are typically not detected and increased moisture in the lower atmosphere is also not well detected. With increased moisture content, the possibility of additional aerosols not observed by the satellite increases as well. For
the WSMR cases in Table 1, Figure 2(e) indicates that the optical depths are primarily in a range
of values between 0.05 – 1.05, although there are a few cases that exceed 1.05. In general, the
cases with the largest effective footprint diameters are associated with low-range optical depths,
but due to the small sample population, there is not a clear statistical relationship. For the 88S
cases in Table 1, the column optical depth is high for the lowest diameter case but remains low to
moderate for the other cases. There is potential for optical depth to be useful at 88S due to a
lower tropospheric height (i.e., below the ICESat-2 threshold) and lack of water vapor in the
atmosphere, but there is currently no apparent trend within this small sample population.

Atmospheric Parameter Summary. The trends described, although based on a relatively small
sample population, suggest that moisture content is inversely related to the footprint diameter for
mid-latitude locations, where the moisture content values are more significant than in the polar
regions. Increased moisture potentially increases forward scattering that widens the full laser
footprint at the surface but lowers the detected energy, relative to a clear atmosphere. That is, the
scattering creates a higher probability that the signal at the footprint outer edges are attenuated
outside the ATLAS field of view. While the connection with atmospheric moisture content at
88S is not apparent, another potential cause of low-level attenuation at 88S is blowing snow in
the near-surface layer. Blowing snow is like an aerosol layer, where the small ice crystals
provide both forward scattering and backscattering on the laser energy. Although not shown, the
case with the lowest diameter indicated moderate blowing snow as identified in ATL09, but
several of the other cases, where the effective footprint diameter was closer to the ensemble
mean, also indicated at least moderate blowing snow as identified in ATL09. Additional data
collection in the coming Austral summer might help to better understand the relationship
between ICESat-2 footprint diameters and both blowing snow and optical depth.

4.3 Seasonality of Returns from 88S

We note that Antarctic CCR results were only available during the austral summer months
(late November through late January) despite nominal pointing control throughout the calendar
year. While it is possible that individual attempts at pointing to a CCR array could be
compromised by attenuation from from blowing snow or snowfall, this seems like an unlikely
explanation for the total lack of CCR returns over the Feb – November months. We note that the
surface reflections during these periods were nominal (Brunt et al., 2019, Brunt et al., 2021) and
suggest that the lack of CCR returns in the Austral winter is associated with frost build up, due to
near-surface atmospheric supersaturation, on either the optical glass or the plastic cap that holds the optical glass. This could be tested by relative humidity measurements at the CCR sites, but we acknowledge the difficulty of making humidity measurements at such low ambient temperatures. CCR signatures are recovered shortly after the sun rises at this latitude, suggesting a thermodynamic explanation.
Figure 2. Comparisons of relative humidity (RH) profiles, specific humidity (SH) profiles, and column optical depth are provided in (a), (b), and (c), respectively, for the 31 May 2019 (8.5 m effective footprint diameter) and 28 March 2020 (12.0 m effective footprint diameter) WSMR cases. The line and gray shading in (c) mark the location of the CCRs. In (d), effective footprint diameter is evaluated with the satellite altitude for WSMR and 88S. Day and night designation is provided as well. Panel (e) shows the column optical depth and panel (f) shows the total SH and maximum RH in the lower atmosphere with respect to effective footprint diameter for WSMR (blue circles) and 88S (blue squares).
5. Summary

We have shown that the passive method of CCR signature analysis provides an on-orbit monitoring capability for geolocation validation of space-based laser altimetry. The results from two study sites indicate that ICESat-2 geolocated photons are accurate to within the mission requirement of 6.5 m. The methodology also provides an assessment of the effective laser footprint diameter. To date, the successful satellite overpasses of the sites indicate that the effective diameter of the ATLAS footprint is 10.9 m ±1.3 m. This study builds on the previous work for the CCR method proof of concept by exploring more statistically robust results for geolocation accuracy and effective footprint diameter retrievals through aggregation of satellite overpass opportunities. This study also provides the initial look into the possible contribution of specific atmospheric conditions to the variation between individual results. Further work, however, is warranted to determine more accurately the correlation between environmental characteristics and the CCR assessments, particularly for the effective footprint diameter. Once these correlations are more precisely known, future CCR signatures could inform on the state of the atmosphere based on signal analysis. Future work will also focus on continued monitoring of the CCR results to assess how they might identify instrument or satellite performance degradation over the course of the mission lifetime.

Acknowledgments and Data Availability

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References


Figure 1.
Figure 2.