Additional Information

Vocabulary

The following terms are used throughout this document:

Spin

Data collected during one full revolution of the lidar. A spin is made up of a collection of scans.

Scan

One vertical line worth of data. A scan is made up of a collection of shots.

Shot

Data associated with a single firing of the laser in a specific direction. A shot may have zero to three returns.

Return

Data associated with one light pulse returned from the scene.

Mixed Return

Return that was the result of returns from two objects that were close enough not to be separable.

Internal Return

A first return of near-zero range caused by reflections within the Honeycomb lidar.

Details

Water Ingress

During the assembly of Laser Bear Honeycomb lidars, their enclosures are pressure-tested to ensure that they are sealed and pass IPX7 testing. With thermal cycling, there can be a leak path that forms near the top of the rotating assembly. Because of its location, this leak path has not caused difficulties in Waymo's application of the Laser Bear Honeycomb lidar because the lidar's rotation axis is vertical, with the rotating assembly on the bottom. There is no data available about other orientations of the lidar. Orientations where the lidar's axis of rotation is far from vertical, or high pressure jets are directed at the interface between the rotating and non-rotating assemblies, are the most likely candidates for water ingress due to this potential leak path.

Point Cloud Quality

Mixed Returns

Returns from objects within about 30-45cm of each other will be mixed and produce a single return somewhere between the location of the two objects.

Range Accuracy

In several cases, as described below, returns from an object may suggest that the object is located at a different distance than its actual distance. This can be accounted for in software.

- **Dim returns**: For returns very close to the detectability threshold, shot-to-shot noise up to +/-5cm can be expected.
- **Bright returns**: Very bright returns (such as from retro-reflectors or mirror-like surfaces) may appear closer by up to ~15cm.

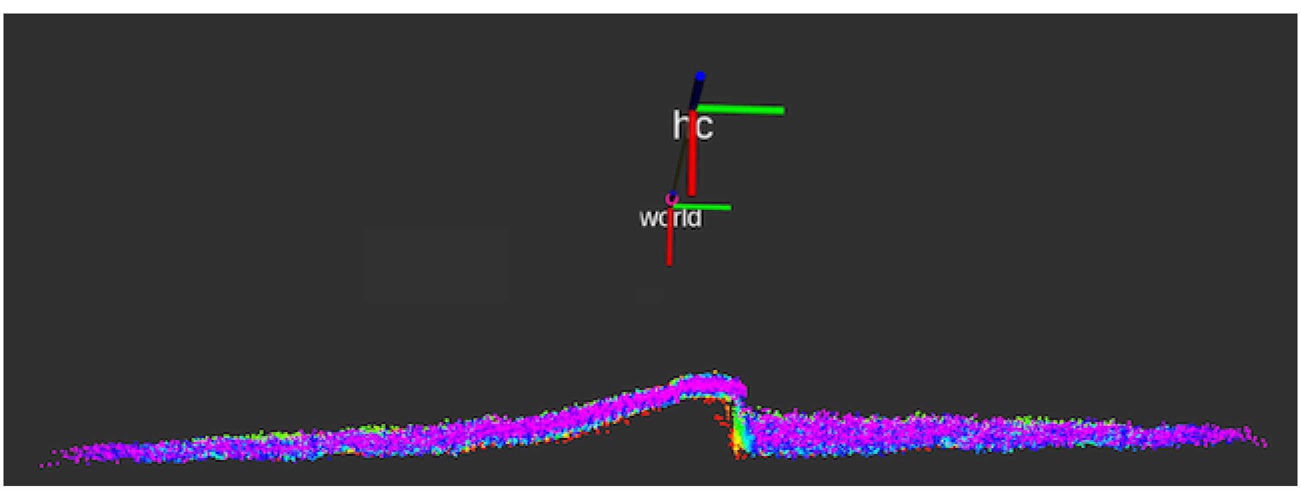

Fig. 1 Top view of target with a vertical retro-reflector strip; the bump or break is where the retro-reflector strip is located.

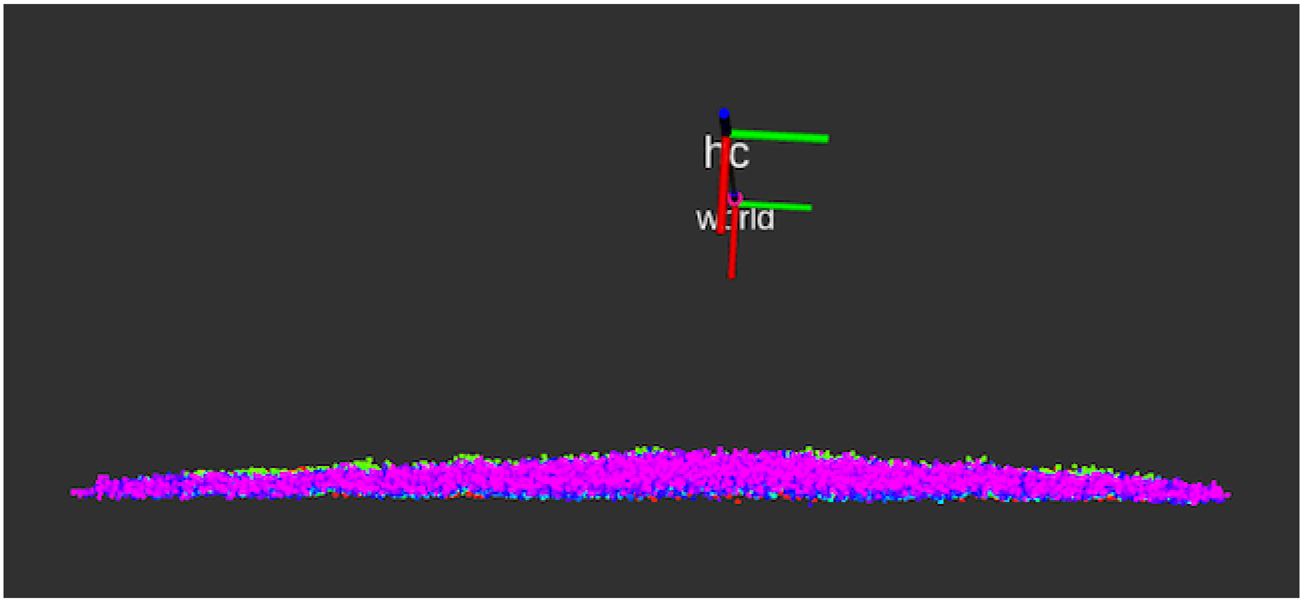

Fig. 2 Top view of the target without any retro-reflectors present.

- **Non-first Returns**: When there are multiple returns to a shot, including when the first return is an internal return, there can be degraded accuracy on all but the first return. For returns that are at least 75cm from the return that precedes it, the return may be up to ~4cm closer than the object that produced it. With less than 75cm separation, the error can increase up to ~20cm.

Internal Reflections

Laser Bear Honeycomb lidars experience internal reflections over some parts of its field of view. These are returns at very close to zero range that are caused by light reflected from internal features in the lidar. Internal reflections are typically found below -45º, between -10º and 0º, and above 10º.

Laser Bear Honeycomb lidars can also experience internal reflections if its windows are dirty and/or wet.

Internal reflections can lead to the first external return to be a non-first return with the associated range error and intensity reduction, particularly for very close objects. For sufficiently close objects (<45cm), the external return and the internal return can be mixed, which is analogous to a large range error.

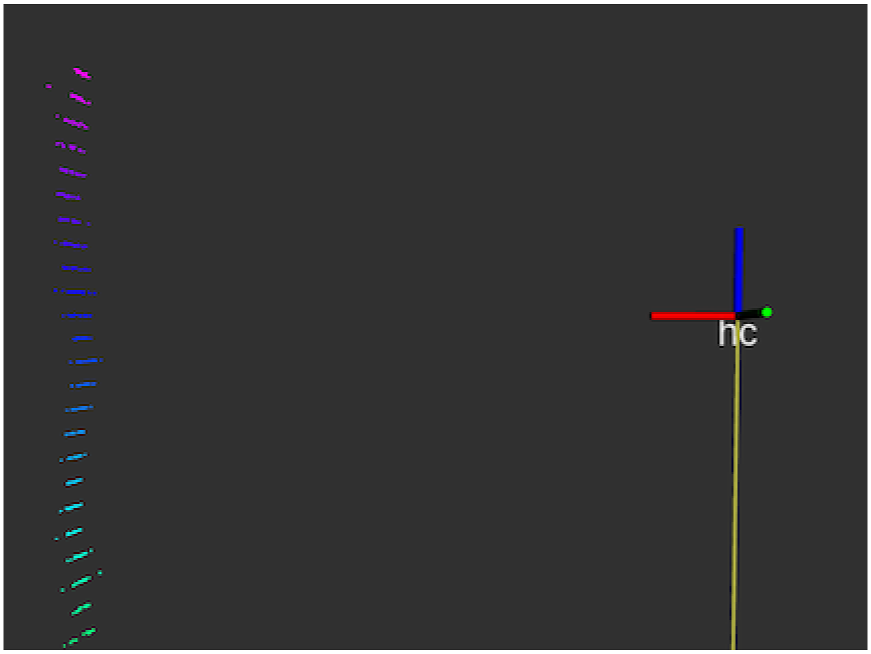

Fig. 3 Wall bulge near 0º.

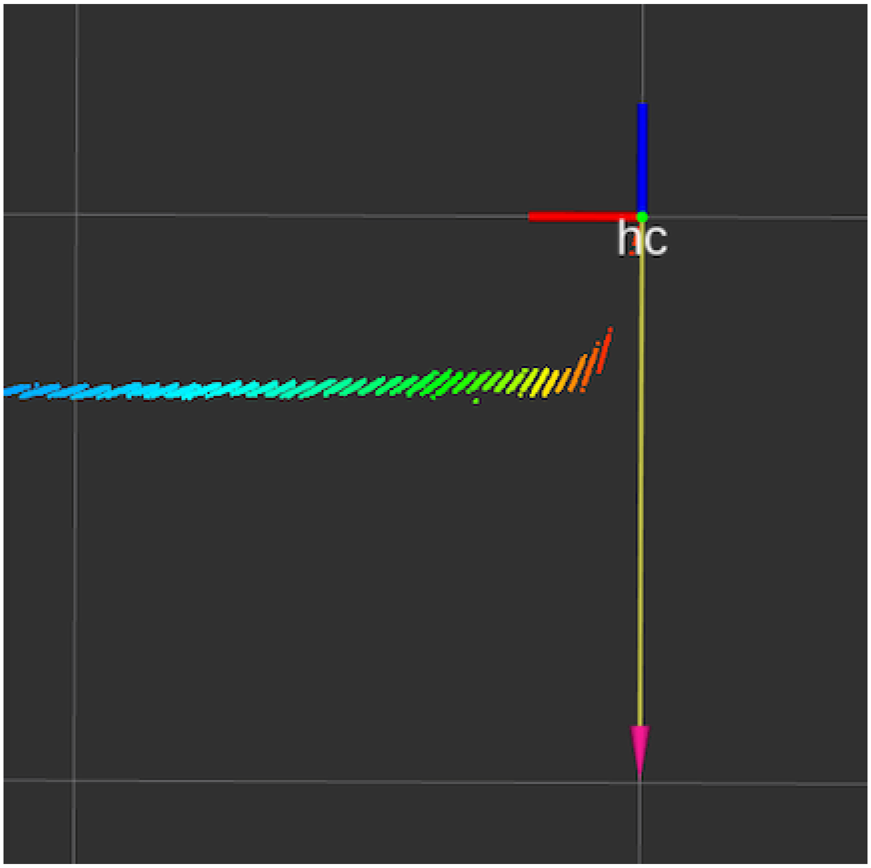

Fig. 4 Ground not flat with lidar 25cm above ground.

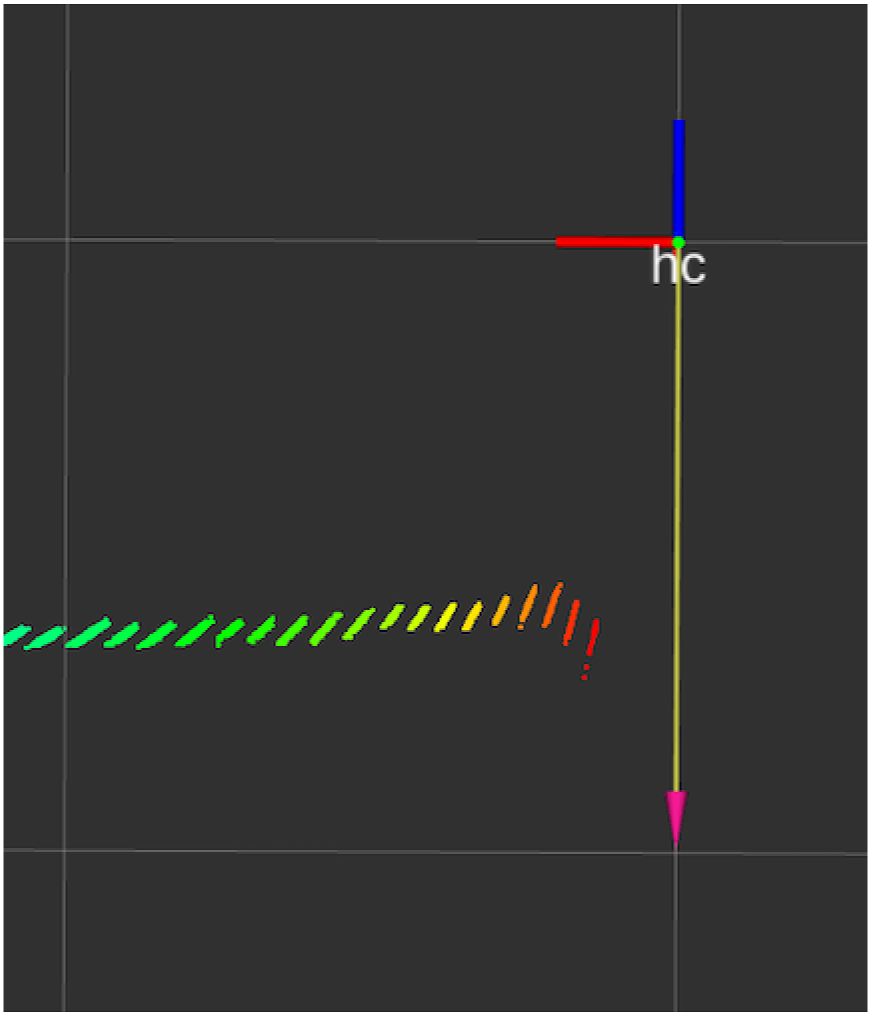

Fig. 5 Ground not flat with lidar 50cm above ground.

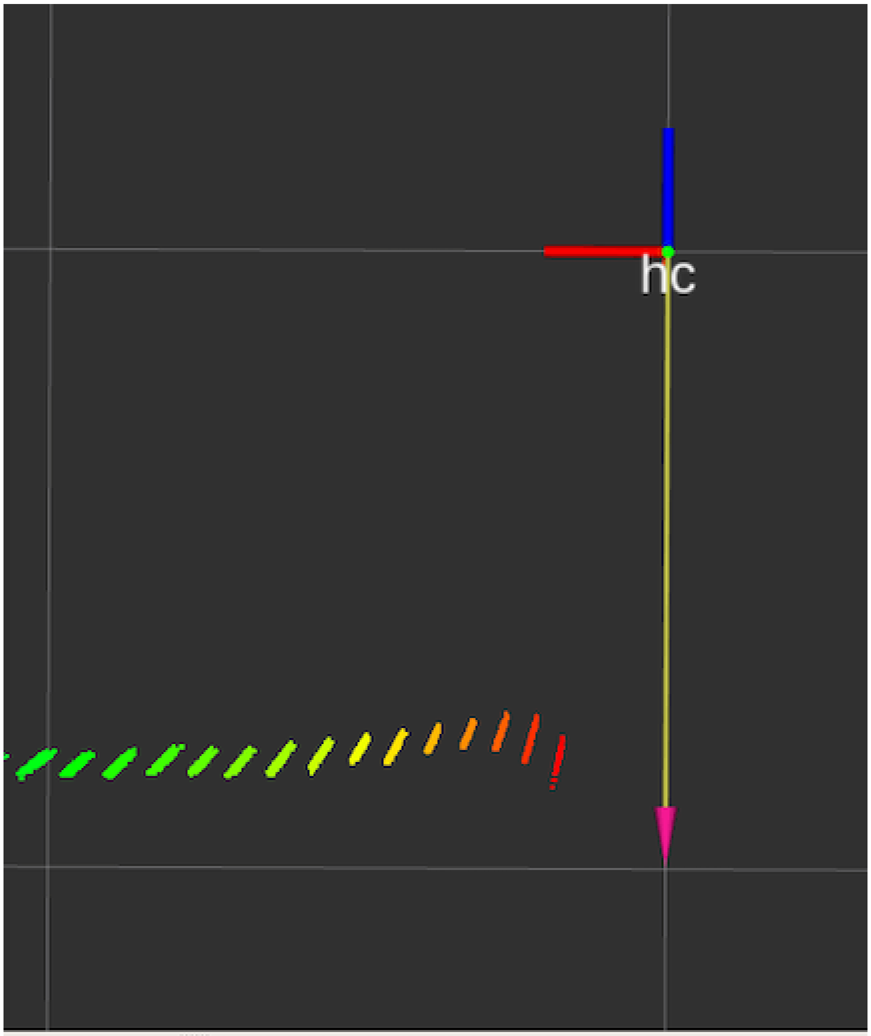

Fig. 6 Ground not flat with lidar 75cm above ground.

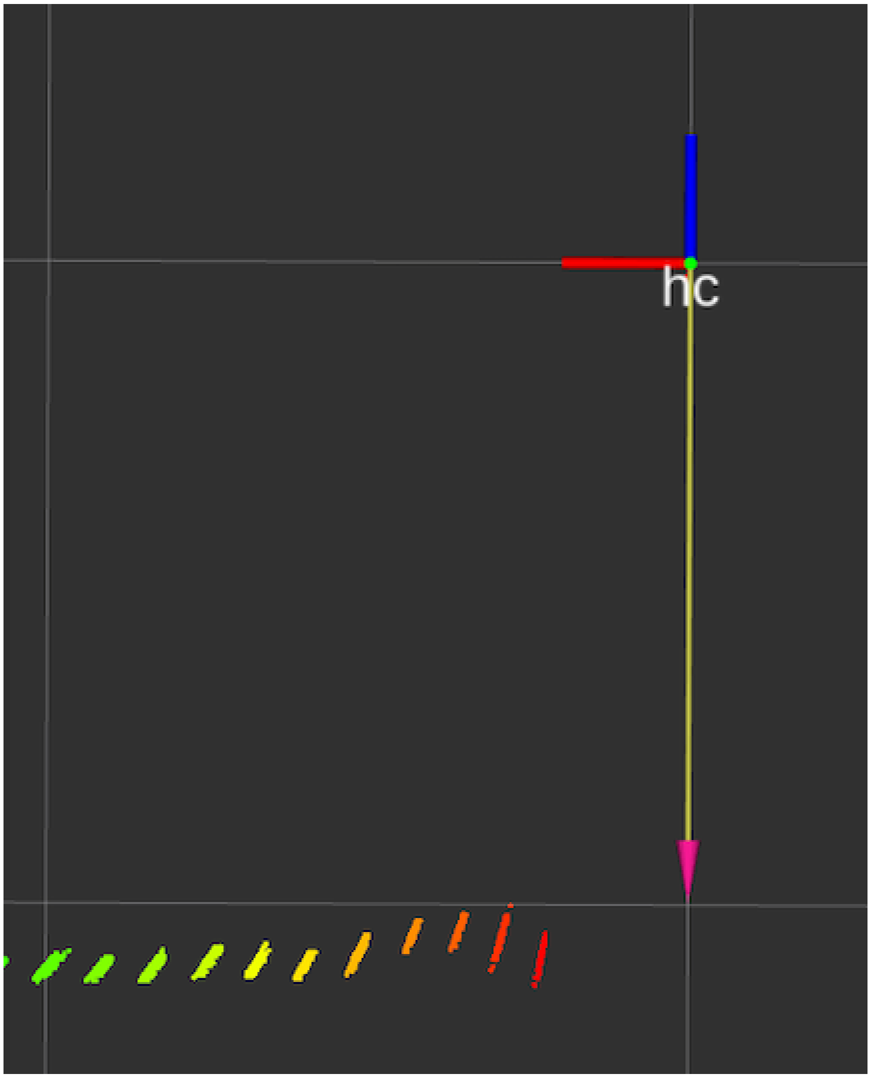

Fig. 7 Ground not flat with lidar 100cm above ground.

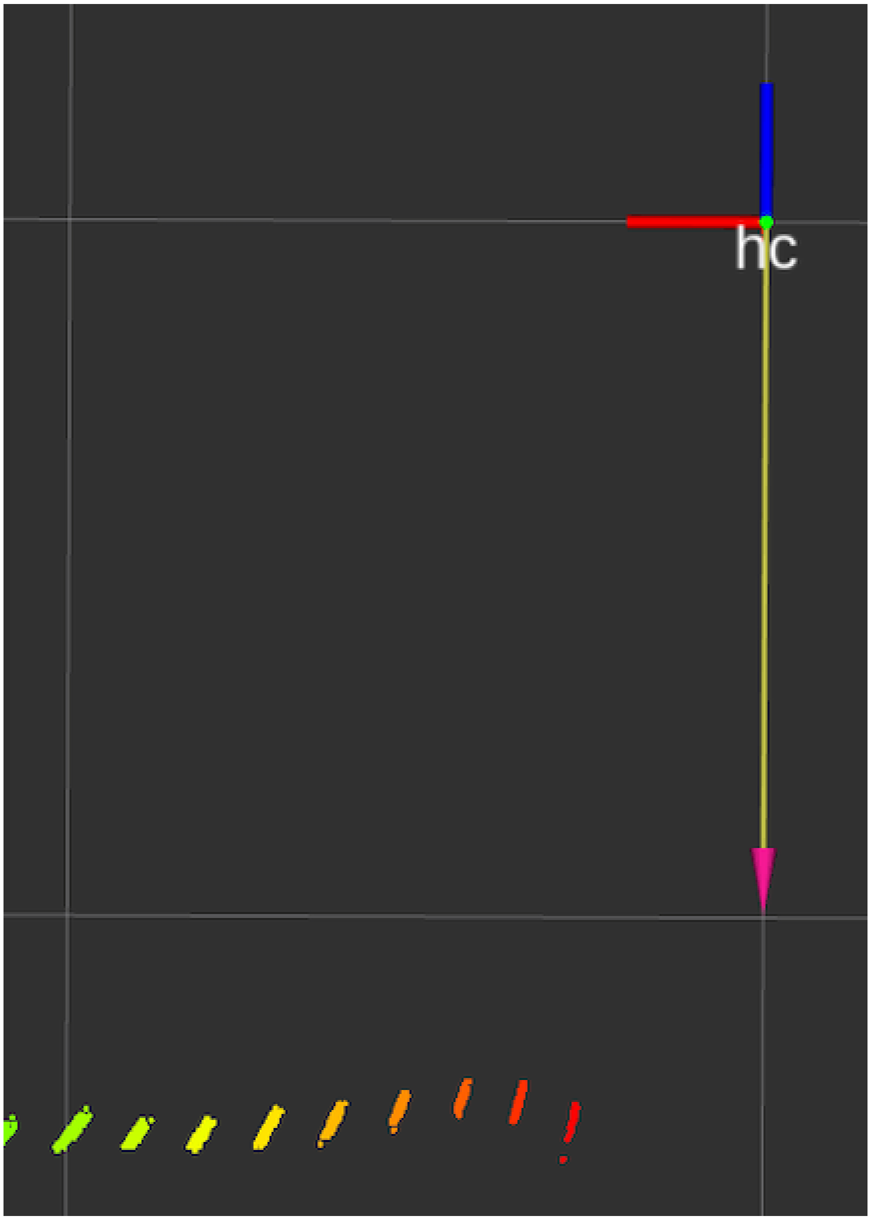

Fig. 8 Ground not flat with lidar 125cm above ground.

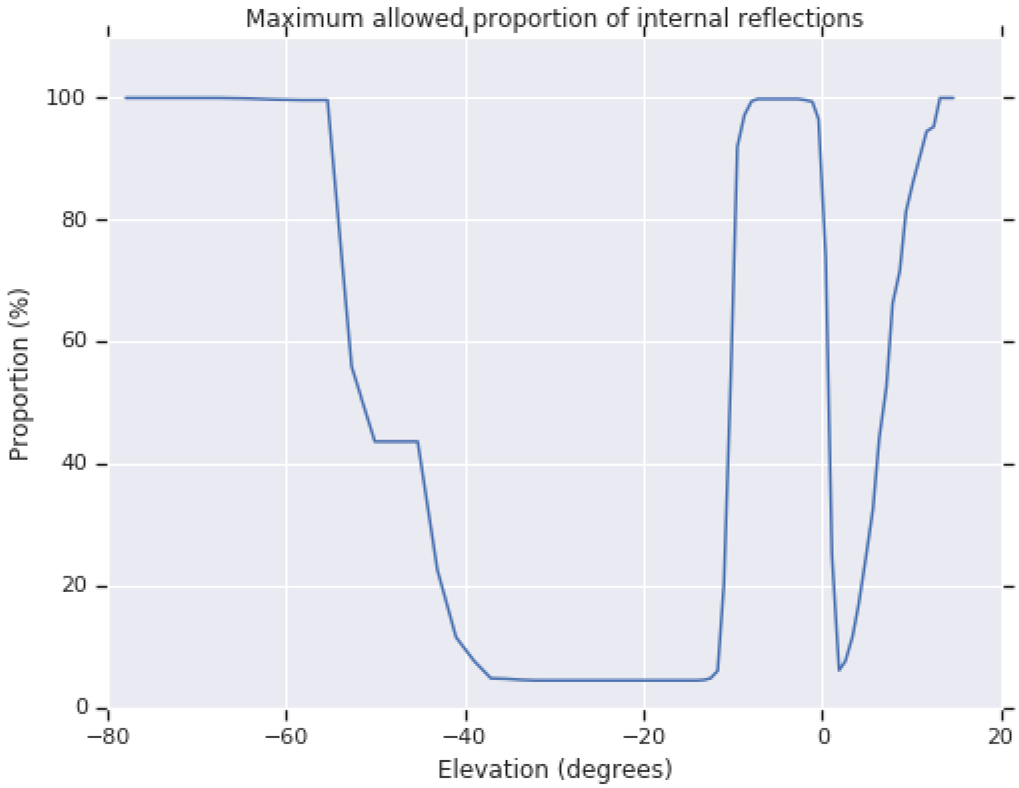

Fig. 9 Maximum proportion of internal reflections allowed during manufacturing.

The graph in Figure 9 describes the expectation of receiving an internal return vs. the elevation angle of the shot. For example, if a shot is fired at -60° the probability of receiving an internal return is 100%. For a shot fired at -20° the probability falls to ~5%. During manufacturing, each Laser Bear Honeycomb lidar is tested to ensure the percentage of internal returns doesn't exceed the limits shown on the graph.

Maximum Range

The Laser Bear Honeycomb lidar's range is quoted at 0º elevation.The range can vary with elevation. The range is at its maximum between ~20º and -55º. Above 20º, it decreases slowly. Below -55º, the range decreases sharply. The intensities reported by the lidar do not currently compensate for these elevation dependencies.

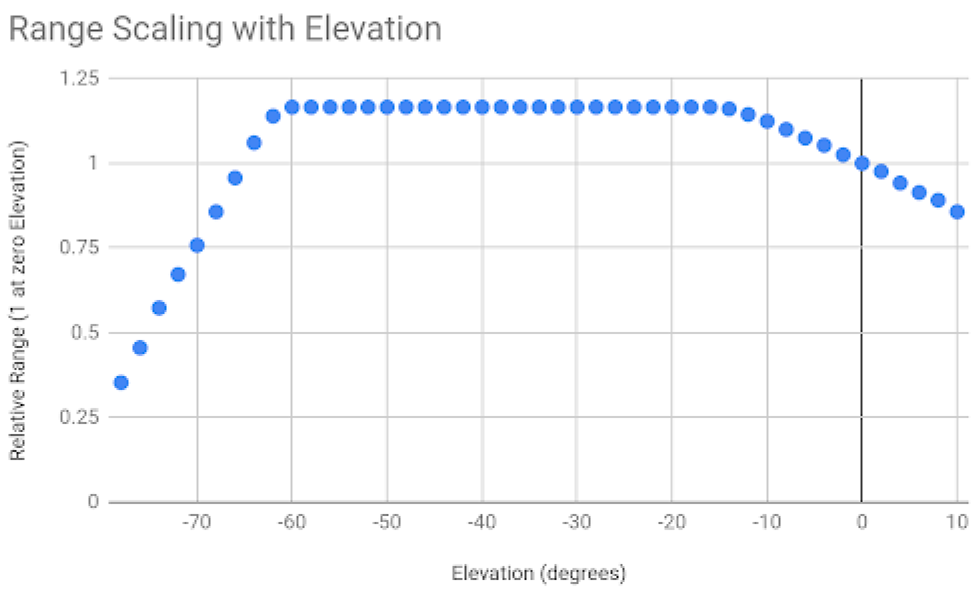

Fig. 10 Range scaling with elevation chart.

Intensity Accuracy

The Laser Bear Honeycomb lidar provides two measures of intensity:

- **Raw intensity**: A measure of intensity directly related to the amount of light received in a light pulse. This intensity may be the best one to use when attempting to find edges in the intensity data.
- **Calibrated intensity**: A measure of intensity partly compensated for non-linearities in the receiver and distance effects. This intensity may allow a coarse comparison between objects in the scene, with the caveats listed below.

Intensity Quality

The quality of the intensity measurement returned by the Laser Bear Honeycomb lidar is low. Factors affecting intensity include:

- **Background light**: The intensity depends on the illumination of the scene.
- **Non-first returns**: When there are multiple returns, all but the first target is illuminated by less than the full intensity of the lidar light beam. The intensity will be reduced accordingly. This effect is not compensated for.

- **Front-back mismatch**: Only the returns from the front window are considered during intensity calibration. There can be significant mismatches between front-side and back-side intensity.
- **Elevation**: The intensity is calibrated at around 5º elevation. No attempt has been made to compensate for elevation-dependent effects.
- **Saturation**: The lidar is highly non-linear. Within ~3m of the lidar, returns can be very close to saturation and most intensity information can be lost. Likewise, retro-reflectors will usually be difficult to distinguish from white targets.
- **Noise**: There can be significant noise shot-to-shot.
- **Dim returns**: For objects at the edge of detectability, noise in the amount of light received shot-to-shot can cause these shots to be either unusually bright or not received. Hence, dim returns may appear brighter than they are.
- **Non-monotonic**: At the high end of the intensity range, the intensity may be non-monotonic with incoming light. This may be the case for retro-reflectors, for example.
- **Angle of incidence**: The calibrated intensity is computed assuming the target is lambertian and normal to the lidar's beam. Specularity of the surface is not compensated for, and the system will not attempt to use Lambert's law to compensate for non-normal incidence.
- **Window cleanliness**: If the lidar's window is dirty, the intensity will be reduced accordingly.

Retro-Reflector Induced Dimming and Range Error (Pre-W20 Hardware Versi Only)

After shooting a retro-reflector at close range, older revisions of the Laser Bear Honeycomb lidar experienced dimming for a few scan lines, resulting in reduced range, reduced intensity, and a range error making objects appear up to ~15cm closer than they actually are. This effect should no longer be present as of hardware revision W20.

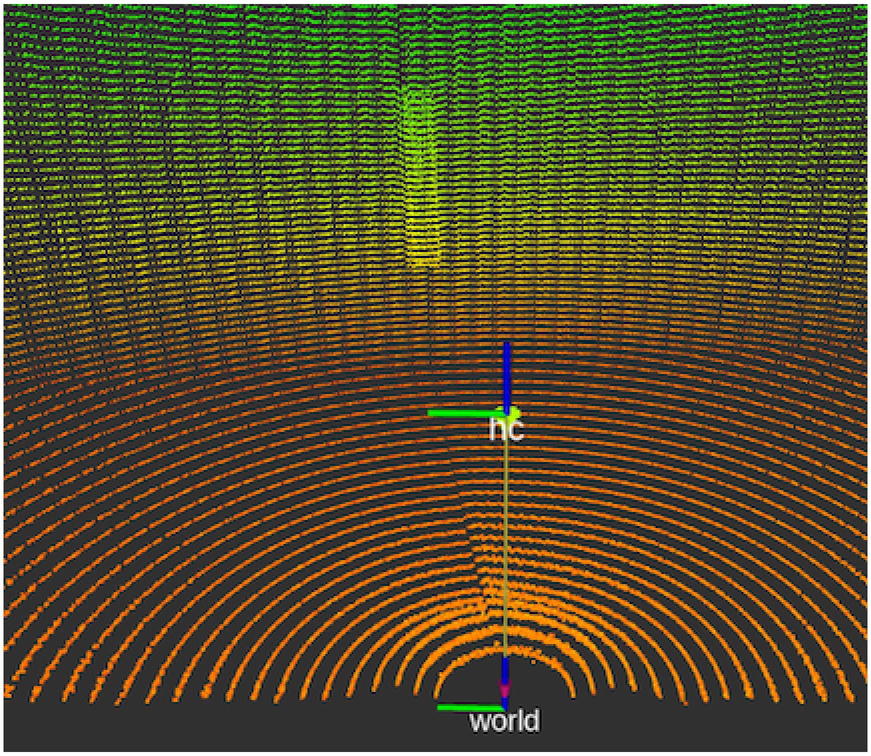

Fig. 11 Displays a wall with a retro-reflector on it. Note the bulge in the ground below the retro-reflector, caused by retro-induced dimming.

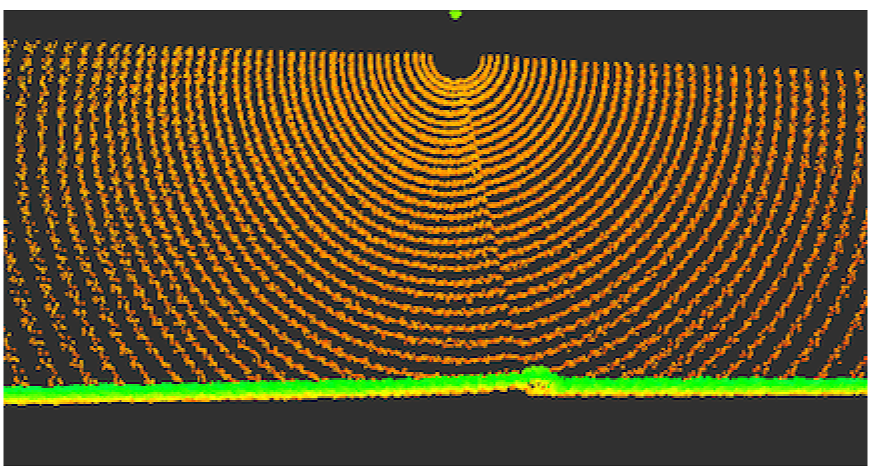

Fig. 12 Same as Fig. 11, top view.

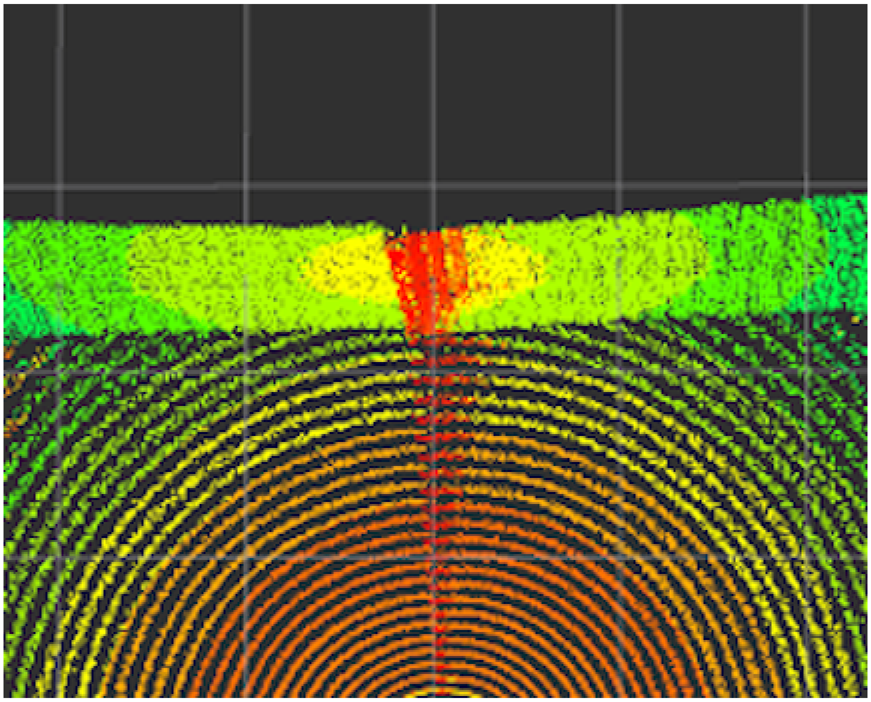

Fig. 13 Retro-reflector target on a white background, top view.

Solar-Induced Dimming

After shooting near the direction of the sun, the Laser Bear Honeycomb lidar will be dimmed for a few scan lines, causing a reduction in range and observed intensity.

Intrinsic Calibration

The Laser Bear Honeycomb lidar's intrinsic calibration is described here (/honeycomb/documents/tips-and-tricks#calibration_process).

Elevation Offset Drift

On a limited set of units, the elevation adjustment drifts by ~1.5º over time scales on the order of a month. The elevation adjustment can be corrected by comparing the front and back point clouds.

Azimuth Calibration Refresh

The azimuth calibration can degrade over long periods of time due to the way the lidar measures its azimuth orientation. If this degradation becomes excessive, the sensor will refuse to start. If this happens, contact lidar-support@waymo.com (mailto:lidar-support@waymo.com).

Distance Offset and Azimuth Offset

The Laser Bear Honeycomb lidar ships from the factory with a distance offset of a few centimeters, and an azimuth offset between the front and back point clouds of up to 2º. We expect customers to adjust these internal parameters as part of their extrinsic calibration process.

Accuracy of Calibration Relative to Mounting Plate

Out of the box, the output of the Laser Bear Honeycomb lidar relative to its mounting plate may vary up to 5º. This can be accounted for by determining transforms during extrinsic calibration.

Noise Returns

Some lidars may produce random noise returns at a rate of up to ~100 returns per spin (1% of shots). This effect is most pronounced at high temperatures, and can be reduced, if necessary, by adjusting the detection threshold, at the cost of reduced range.

High Magnetic Fields

Operating the lidar in strong magnetic field environments can hinder the lidar’s ability to measure its position. If excessive offset is detected, the lidar will blank its point cloud to avoid returning incorrect readings.

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