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Avoid Incidents with Incidence

When collecting or using LIDAR data, the location of the scanner/sensor relative to the object of interest and the geometry of the object itself can influence the ability to receive returns from laser pulses. These factors can also affect the resulting accuracies of the acquired points. This concept has important implications when selecting the best platform for a particular application. Airborne and helicopter systems will generally have the best look angle for gently sloping topography. Terrestrial systems will have improved results on building facades and cliff faces. An easy way to visually understand the concepts behind grazing\incidence angles (how the light hits and reflects from the surface) is to shine a flashlight on a wall and look at the distribution of the light. When you shine it directly orthogonal to the wall, the light pattern is circular. However, when you shine it obliquely, the light produces an ellipse that will become more oblong with increasing obliqueness. Other factors that are important to the effects of grazing are the beam exit diameter and divergence.

Now for the nerdy math to describe what is going on! (We will keep it to 2D derivations for clarity in this article). For the presented derivations, based on scanning a sea cliff, all elevations are relative to the cliff base. Simple geometry can be used to determine the angle of incidence (θ, angle between the laser beam and surface normal) and grazing angle (γ, angle between the laser beam and cliff surface). Lower incidence angles and higher grazing angles indicate that the reflection is more direct to the surface.

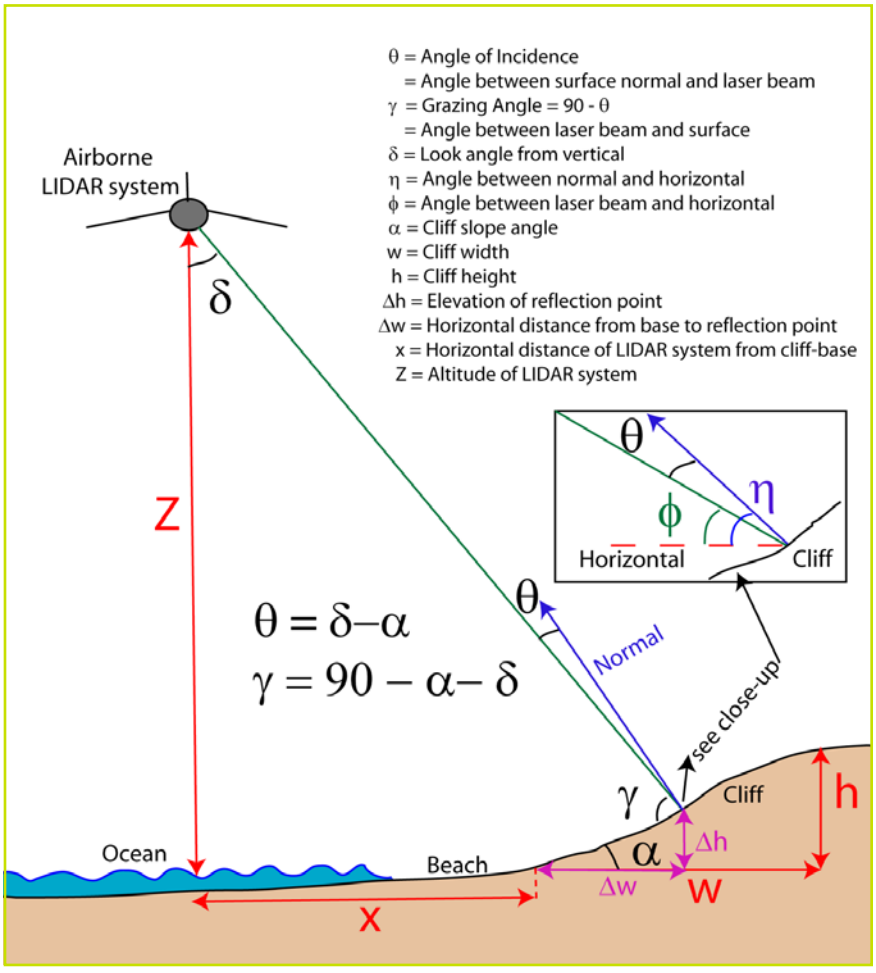

Figure 1. Schematic showing calculation of incidence and grazing angles for airborne LIDAR and definitions of variables.

Figure 1 shows the setup and calculation for airborne LIDAR and **Figure 2** shows the setup and calculation for terrestrial laser scanning (TLS). While the geometry and calculations would be the same between the airborne and terrestrial scanners, the equations for each are simplified in a different manner.

First, the general cliff slope can be calculated through trigonometry:

$$\alpha = \tan^{-1}(h/w) \quad (1)$$

The angle of the cliff surface normal from horizontal (η) is defined as:

$$\eta = 90° - \alpha \quad (2)$$

Next the angle of the laser beam from vertical (δ) for airborne scanning is calculated by:

$$\delta = \left| \tan^{-1}\left[(x+\Delta w) / (Z-\Delta h)\right] \right| \quad (3)$$

For the TLS, the scanner is typically close to the same elevation as the base of the cliff, so Z ~ 0. Hence, δ would be negative for TLS without the inclusion of the absolute value function. The beam angle (ϕ) from horizontal can be calculated as:

$$\phi = \left| 90°-\delta \right| \quad (4)$$

The definition of the incidence angle is the angle between the normal and the beam angle. Thus,

$$\theta = \eta-\phi \quad (5)$$

Note that φ is upward/positive from horizontal for Z> Δh (airborne) and negative from horizontal for Z≤ Δh (terrestrial scanning). So for airborne LIDAR (Z> Δh):

$$\theta = (90°-\alpha) - (90°-\delta) \quad (6a)$$

$$\theta = \delta - \alpha \quad (7a)$$

And for terrestrial (Z≤ Δh):

$$\theta = (90°-\alpha) + (90°-\delta) \quad (6b)$$

$$\theta = 180°- \alpha - \delta \quad (7b)$$

The grazing angle can then be calculated by:

$$\gamma = 90 - \theta \quad (8)$$

So for airborne LIDAR (Z> Δh):

$$\gamma = 90° - \alpha - \delta \quad (9a)$$

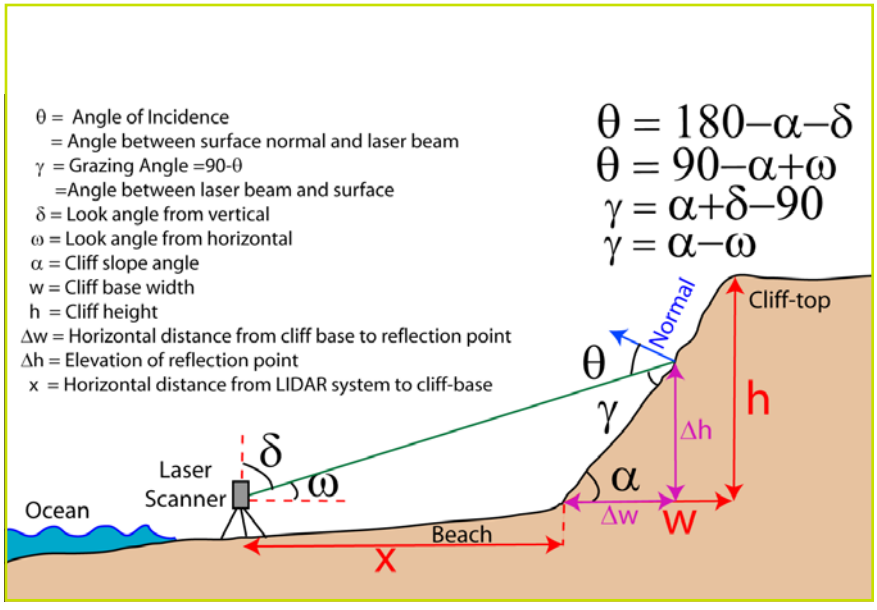

Figure 2. Schematic showing calculation of incidence and grazing angles for TLS

And terrestrial (Z≤ Δh):

$$\gamma = \alpha + \delta - 90° \quad (9b)$$

Additionally, for TLS (Z≤ Δh), the calculations can be simplified by assuming the scanner is directly horizontal from the cliff base and using the angle of the laser beam from horizontal, ω, instead of δ. ω is simply calculated by:

$$\omega = 90°- \delta \quad (10)$$

or:

$$\omega = \left| \tan^{-1}\left[(Z-\Delta h) / (x+\Delta\omega)\right] \right| \quad (11)$$

By forming a triangle between the scanner, a point directly horizontal from the scanner on the cliff base (Z = 0), and the point of reflection, and using the identity that the sum of the three angles of a planar triangle is 180°, the grazing angle can be calculated:

$$180° = \omega + (180°-\alpha) + \gamma \quad (12)$$

$$\gamma = \alpha- \omega \quad (13)$$

And the incidence angle can be calculated by:

$$\theta = 90°-\gamma=90°-(\alpha-\omega)=90°-\alpha+\omega \quad (14)$$

Now that we have discussed the math, let us calculate some values to determine the influence of these parameters on the resulting scanning grazing angles. **Figures 3** and **4** show calculated grazing angles based on various configurations of cliff geometry and scanner position. In general, airborne LIDAR has better grazing angles for gentle cliff slopes, while TLS has better grazing angles for steep cliff slopes. **Figure 3** shows the grazing angles for the mid-height of the cliff, while **Figure 4** shows the worst-case scenario for terrestrial LIDAR at the top of the cliff. Note that for low values of x/h, scanning is performed too close to the cliff, reducing grazing angles. Also, the airborne appears consistent between plots, however, for a fixed airplane position, δ would vary between the

mid-height of the cliff and the top, so a different value should be calculated for each position.

Now, why is this important and why go through the math? Ultimately, understanding these fundamentals is important when planning airborne or helicopter LIDAR flight paths or terrestrial scan setup locations to ensure quality data. It is also something important to verify when using a dataset provided by someone else. One of the challenges with LIDAR is the accuracy of every single point varies. Poor scanning geometry can have a much more significant effect on overall accuracy (and resolution) than sensor noise and geo-referencing error. In some cases, you may have no option but to graze because of limited locations you can physically setup at. However, you should be aware of how that will degrade your overall data quality and consider that in your error validation and reporting. When you provide error estimates based on targets and check points that are orthogonal to the scanner, you are not really showing what the quality is in the oblique sections of your data.

To summarize, avoid incidents of poor data by properly planning your surveys so that you can have improved incidence angles!

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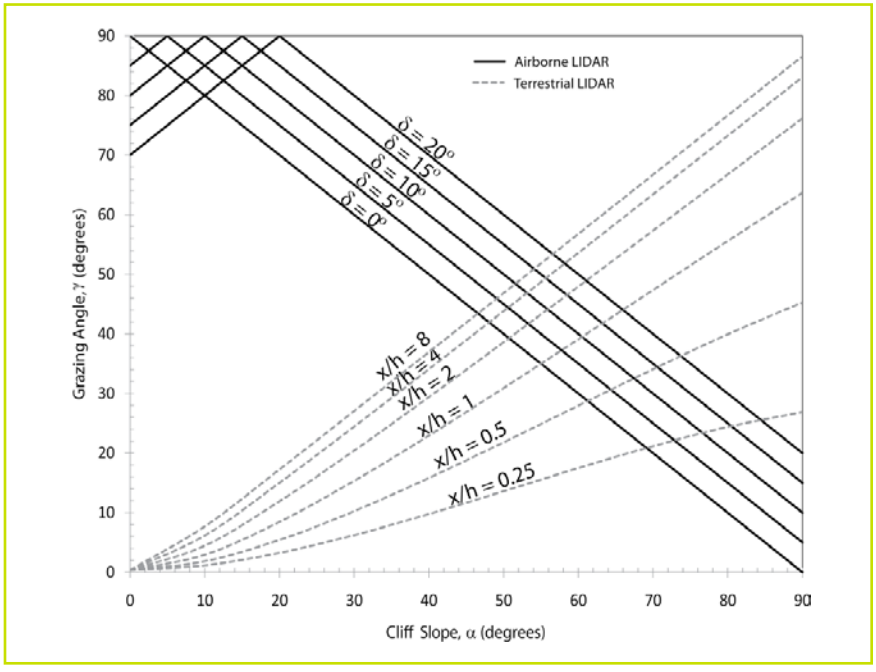

Figure 3. Grazing angles at mid-height of a cliff for airborne and terrestrial LIDAR systems based on geometric configurations.

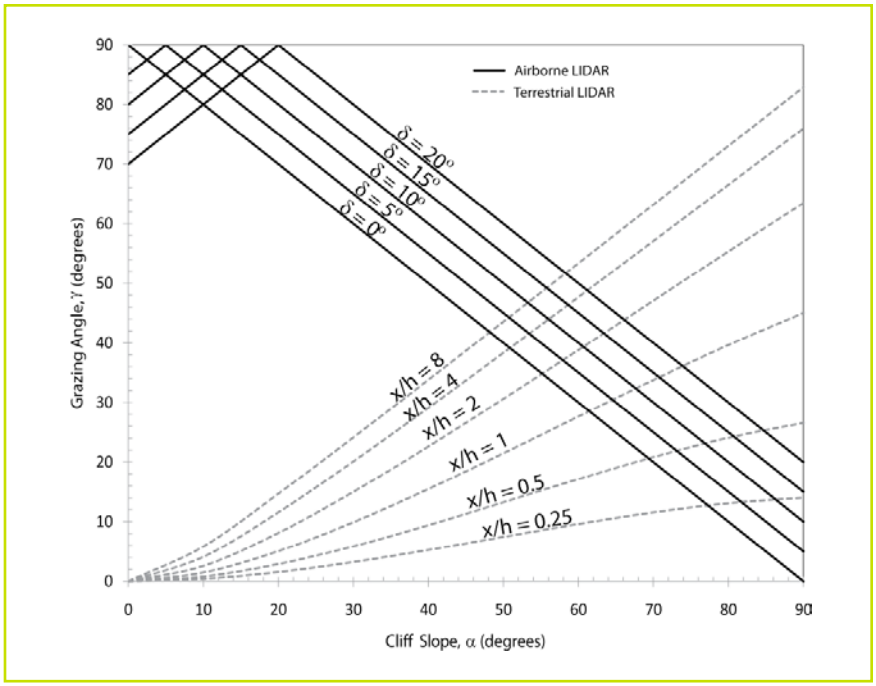

Figure 4. Grazing angles at top of a cliff for airborne and terrestrial LIDAR systems based on geometric configurations. Note that the cliff top provides the worst-case grazing angles for terrestrial LIDAR and the best for airborne.