1.15 Lidar Sensors From Space
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1.15.1 Introduction

Lidars are similar to radars in remote sensing but at optical wavelength. Because of the much shorter wavelength, lasers can be modulated much faster and the laser beams can be collimated to a much smaller spot on the ground. As a result, lidars generally have much higher temporal and spatial resolutions, and smaller instrument sizes. However, lidar signal cannot penetrate dense clouds or soil surface like radars. Lidars require much tighter bore-sight and pointing alignment control. Lidar technologies are still evolving, while radar technologies are relatively more mature at present.

Lidars detect the backscattered laser light from atmosphere and surfaces and infer the target characteristic from the changes in the received signal with respective to the transmitted ones as depicted in Fig. 1. Lidars measure target ranges from the time delays of the received laser pulse, or time-of-flight, in reference to the transmitted laser pulses. Lidars measure the surface slope within the laser footprint from the pulse broadening of the received pulse and long baseline slope from the range difference between the successive range measurements. Lidars measure surface roughness from the changes in the shape of the reflected laser pulses. Lidars measure vegetation coverage and tree canopy heights from the vertical profiles of the received pulse waveforms. Lidars measure surface reflectance to the laser light from the ratio of the received to the transmitted laser pulse energies. Lidars measure atmosphere backscattering cross sections from the amplitude and the temporal profile of the received waveform. Lidars measure the wind speed by the Doppler shift in the wavelength of the backscattered laser signal. Lidars can measure the atmosphere and surface simultaneously with the same laser pulses. With a proper choice of the laser wavelengths, lidar can measure the spectral absorption and consequently the abundance of the elements of interests in the Earth atmosphere or surface.

Lidars can have multiple laser beams and receivers to multiply the coverage and provide additional information about the target. Multibeam lidars are used for surface elevation and vegetation measurements to improve coverage and give along-track and cross-track slope measurements. Scanning lidars are now routinely used on airplanes to provide 3-D images of the land and vegetation. Multispectral lidars are used to measure the atmosphere backscattering to provide additional information about the atmosphere composition. Differential absorption lidar (DIAL) is used to measure the total column atmosphere absorption by certain atmosphere gas, such as methane, by comparing the received signals at online and offline wavelengths of the gas absorption line.

In the rest of this chapter, we will describe the three most widely used lidar sensors at present. These are surface elevation lidars, atmosphere backscattering lidars, and spectral absorption lidars. Surface elevation lidars record and analyze surface and vegetation returns and often called laser altimeters. Atmosphere backscattering lidars continuously record the backscattering from the molecules and particles as the laser pulses propagate through the atmosphere, including cloud and aerosol lidars, wind lidars, etc. Spectral absorption lidars measure the surface or atmosphere return at particular laser wavelengths about the spectral absorption line of the interested constituents. We will describe each type of lidar sensors, including principle of operation, calculations of the measurement precision, special technology challenges, and history and future directions of each type of lidar sensors for space.
1.15.2 Surface Elevation Lidars

1.15.2.1 Principle of Operation

Surface elevation lidars measure the laser pulse time-of-flight and hence the distance from the spacecraft to the surface and then solve for the surface elevation with the knowledge of the spacecraft orbit position with respect to the center of the mass of the Earth, as shown in Fig. 2. The lidar measurement gives a vector from the spacecraft to the Earth, with the length of the vector determined from the laser pulse time-of-flight and the direction of the vector provided by the spacecraft orbit position and orientation at the time of the laser pulse emission. One can solve for the intersecting point of this vector with Earth surface and the elevation at intersection point on the surface. A global surface elevation map can be obtained from continuous measurements as the spacecraft orbits around the Earth. The spatial resolution is determined by the laser footprint size, which is determined by the laser beam divergence angle and the spacecraft altitude. The lidar measurement coverage on the surface is determined by the laser pulse repetition rate, orbit spacing, and duration of the mission. Because of the short wavelength, laser beams can be collimated to a much narrower divergence angle and hence smaller footprint on the surface, typically tens of meters in diameter. The laser pulse rate is limited by the type of lasers used, the receiver sensitivity, and the available instrument electrical power. Another limiting factor is the atmosphere backscattering from the adjacent laser pulses that could corrupt the surface returns. For Earth atmosphere, this limits the laser pulse rate to about 10 kHz so that cloud returns from one laser pulse diminish before the next laser pulse enters the atmosphere.

The spacecraft orbit position and pointing angle have to be determined independently using data from star trackers, gyros, and other spacecraft tracking data. A Global Position System (GPS) may be used to determine the spacecraft position to a few centimeters and time to microseconds with respect to the GPS time or a commonly used timing standard.

The surface elevation at the intersect of the laser beam and the Earth surface can be solved using the law of cosine once the spacecraft orbit position, the pointing angle, and the distance traveled by the laser pulse are known, as depicted in Fig. 3.

Lidar receivers have to precisely measure the time interval from the laser pulse transmission to the received laser pulse. A leading edge threshold crossing detection receiver is simple to implement but gives rise to a measurement bias, known as range walk, due to pulse amplitude fluctuation from the constantly varying atmosphere transmission and surface reflectance. The range walk may not be correctable unless the surface slope and the received pulse width are known by other independent measurement. One simple method to avoid the range walk is to measure the threshold crossing time at both the leading and falling edges and take the average of the two as the pulse arrival time. A more precise method is to digitize the pulse waveforms and calculate the pulse centroid times, or fit the received pulse waveform to a known pulse shape and take the center or the centroid of the pulse wave from the best fit. The laser emission time may be measured using the same detector and the waveform digitizer to avoid time skews between the transmitted and received laser pulse measurement channels.

The on-board clock oscillator frequency has to be precisely known since the laser pulse time-of-flight measurement measure by the lidar is given in the number of clock cycles that has to be converted to time. One method to keep track the lidar clock time is to
Fig. 2  Concept of lidar surface elevation measurements.

Fig. 3  Determination of the surface elevation from lidar measurements.
calibrate the lidar oscillator frequency with respect to the spacecraft clock which is monitored via the mission control on ground. The spacecraft usually sends its mission elapsed time (MET) to each payload instrument in the form of 1 pulse per second (1 pps) time marks. The lidar can either phase lock its clock to the MET or monitor its clock frequency by counting the number of clock cycles in between the 1 pps time marks of the MET. The GPS receiver also sends out 1 pps time marks which can be used to calibrate the lidar clock. As mentioned earlier, the lidar receiver has to measure the epoch time of the laser pulse emission in order to determine the spacecraft orbit position when each laser is fired. The epoch time of laser emission just needs to be accurate enough to geolocate the laser spot on the ground to a fraction of the laser footprint size. For Earth-orbiting satellites, the ground track speed is about 7 km/s and laser footprint size is typically tens of meters. Therefore the epoch time of the laser pulse emission needs to be accurate to within hundreds or microseconds. This is usually achieved with a timer that measures the laser triggering time to the previous MET or GPS 1 pps tick.

It is critical to precisely determine the laser beam pointing angle which in turn determines the location of laser footprint on the ground. Over a sloped surface, a laser footprint location error is directly translated into a range measurement error, since the actual range measurement is made to a point up or down the slope from where it was thought to be, as shown in Fig. 3. This is usually the dominant error source for the surface elevation lidar measurements. The same is true for lidar measurement at a slant angle from the surface normal vector. This is why most surface elevation lidars in orbits have the laser beam pointed in nadir direction. For a large sized lidar, the laser beam pointing angle may vary with temperature gradient across the instrument which makes it difficult to determine the laser pointing angle from the spacecraft start trackers and gyros. A precision surface elevation lidar has to actively measure the laser beam pointing angle with respect to the star field. One way to do this is to split a small portion of the outgoing laser beam and fold it into a start tracker to superimpose the laser spot onto the star field.

Fig. 4 shows a block diagram of the Geoscience Laser Altimeter System (GLAS) on the Ice, Clouds, and land Elevation Satellite (ICESat) (Sun et al., 2013). It consists of four main subsystems, the laser, the receiver, the timing electronics, and the stellar reference system. GLAS also provides atmosphere backscattering measurements which we will describe in the next section.

Surface elevation lidars have also been used for multiple ground target detection such as simultaneous tree canopy profiling and ground detection. Surface elevation lidar can also be used to measure the time-of-flight of both the water surface return and the ocean bottom return for bathymetric studies. The receiver in these cases has to have a wide dynamic range and measure the time-of-flight of entire backscattering profile. For bathymetric measurement, the receiver may have to histogram the data along...
the ground track to detect the much fainter signal reflected by the ocean floor. The maximum depth of ocean floor measurements are still limited to coastal areas at present because of the much higher attenuation to the laser light by the ocean water.

1.15.2.2 Measurement Precision and Accuracy

The lidar measurement precision is mostly affected by the receiver signal-to-noise ratio (SNR). The received signal is governed by the lidar link equation (Fernandez Diaz et al., 2013; Gardner, 1982, 1992)

\[ E_r = E_n \frac{\rho_s A_r}{R^2} h f_t \]  

(1)

where \( E_r \) and \( E_n \) are the received and the transmitted laser pulse energy, \( \rho_s \) is the surface reflectance, \( A_r \) is the receiver aperture area, \( R \) is the range from the spacecraft to the surface, \( T_a \) is the one-way atmosphere transmission, and \( h \) is the receiver optics transmission. It is assumed that ground surface reflection is uniform in all directions (Lambertian) and the laser beam divergence angle is smaller than the receiver field of view (FOV) that the detector sees the entire laser footprint on the surface. The number of the detected signal photon over the integration time can be expressed as

\[ \langle n_{\text{sig}} \rangle = \frac{\eta_{\text{det}} E_r}{\eta_{\text{det}} h f} \]  

(2)

where \( \eta_{\text{det}} \) is the detector quantum efficiency and \( h f \) is the photon energy.

The average background noise photons can be calculated as

\[ \langle n_{\text{bg}} \rangle = I_{\text{solar}}(\lambda_{l}) \Delta \lambda_{bg} \rho_s \left( \frac{\text{FOV}}{2} \right)^2 A_r T_a^2 \eta_r \]  

(3)

where \( I_{\text{solar}}(\lambda_{l}) \) is the solar spectral irradiance in watts per unit area per unit spectral bandwidth, \( \lambda_{l} \) is the laser wavelength, \( \Delta \lambda_{bg} \) is the receiver optical bandwidth, and \( \text{FOV} \) is the full-angle receiver field of view.

The noise of a lidar receiver consists of the shot noise from the quantum nature of light detection and the electronics noise of the preamplifier. The electronics noise is the dominant noise source unless there is internal multiplication gain for the primary photodetectors to rise above the electronics circuit noise. The photoelectron multiplication is a random process that also introduces an excess noise. The electronics noise of the preamplifier can be modeled as white Gaussian noise that is independent of the signal and appear additive to the total detector output. The photon detection shot noise and the photoelectron multiplication excess noise are multiplicative which increases with the amount of light onto the detector and the detector dark noise. Unlike radar, the lidar receiver noise is not a stationary additive noise but a function of the received signal, which complicates the receiver performance analysis. The variance of the total noise in number of detected photons can be expressed as (Gagliardi and Karp, 1995)

\[ \sigma_n^2 = F_{\text{ex}} \left( \langle n_{\text{sig}} \rangle + \langle n_{\text{dark}} \rangle + \sigma_{c}^2 \langle G \rangle^2 \right) \]  

(4)

where \( F_{\text{ex}} = \langle G^2 \rangle / \langle G \rangle^2 \) is the excess noise factor, \( \langle G \rangle \) is the average photoelectron multiplication gain, \( \langle n_{\text{dark}} \rangle \) is the average number of dark counts, or the dark of the detector, and \( \sigma_{c} \) is the standard deviation of the electronics circuit noise, which mostly comes from the preamplifier immediately after the photodetector. The detector dark count can be calculated by dividing the dark current by the electron charge multiplied by the detector integration time. The mean and variance are equal for the shot noise from the signal, background light and the detector dark count noise.

There are two receiver SNRs, one is the ratio of the mean signal to the standard deviation of the noise floor before the signal rises and the other is the ratio of the mean signal to the standard deviation of total noise when the signal is present, that is

\[ \text{SNR}_0 = \frac{\langle n_{\text{sig}} \rangle}{\sigma_n(0)} = \frac{\langle n_{\text{sig}} \rangle}{\sqrt{F_{\text{ex}} \langle n_{\text{sig}} \rangle + \langle n_{\text{dark}} \rangle + \sigma_{c}^2 \langle G \rangle^2}} \]  

(5a)

and

\[ \text{SNR}_1 = \frac{\langle n_{\text{sig}} \rangle}{\sigma_n(\langle n_{\text{sig}} \rangle)} = \frac{\langle n_{\text{sig}} \rangle}{\sqrt{F_{\text{ex}} \langle n_{\text{sig}} \rangle + \langle n_{\text{dark}} \rangle + \sigma_{c}^2 \langle G \rangle^2}} \]  

(5b)

In the case of single-photon detectors, the excess noise becomes unity and the circuit noise contribution becomes negligible (i.e., \( F_{\text{ex}} = 1 \) and \( \langle G \rangle \rightarrow \infty \)), and Eqs. (4) and (5) still apply. The probability of signal detection is a function of both SNR$_0$ and SNR$_1$, while the lidar measurement precision after the signal is detected is mainly a function of SNR$_1$.

Another factor that affects the receiver SNR is the laser speckle noise. Laser speckle noise occurs at lidar receivers when illuminating a diffusive surface with a laser (Goodman, 1965). The reflected laser lights from different points within the laser footprint interfere and form a speckle pattern (bright and dark cells) at the entrance of the receiver telescope. The number of speckle cells enters the telescope and on to the detector is a random variable which gives rise to another signal intensity noise. Speckle noise is independent of the laser power and can become the dominant noise source when the laser signal power is strong. The variance of the normalized signal amplitude due to laser speckle can be approximated by the ratio of the receiver telescope area to the average speckle size at the telescope entrance (Goodman, 1965, 1973). For diffraction-limited transmitted laser beam, the average laser
speckle size is approximately equal to the outgoing laser beam size at the e^2 points (Gardner, 1982, 1992). The receiver SNR due to laser speckle alone can be approximated as

$$SNR_r = \sqrt{ \frac{A_c}{A} } \frac{\phi_{tel}}{\phi_{laser}}$$

where \(A_r\) is the receiver aperture area and \(A_c\) is the speckle coherence area, \(\phi_{tel}\) is the diameter of the receiver telescope, and \(\phi_{laser}\) is the diameter of the transmitted laser beam at the e^2 points. For direct detection lidar, speckle noise can be reduced by increasing the receiver telescope size and reducing the laser beam size. A larger receiver telescope not only helps to collect more signal but also reduces the speckle noise. However, reducing the laser beam size causes an increase in the laser footprint size on surface and reduces the spatial resolution of the lidar measurement. For coherent lidars, the received laser light has to be temporally and spatially coherent with the reference laser (local oscillator), and the receiver telescope size has to be smaller than a speckle cell. This is why the laser beam collimation telescope needs to be as large as the receiver telescope or share the same telescope and the speckle SNR is less than unity. The speckle noise can be treated as an independent and identically distributed random variable. One can average the measurement results from a number of laser pulse measurements to achieve the necessary measurement performance.

The SNRs are important characteristics of the lidar receiver but not sufficient to determine the lidar measurement performance without knowing the actual probability density functions of the signal and noise. The photon detection shot noise follows a Poisson distribution, and the circuit noise can usually be modeled to have a Gaussian distribution. The two can be assumed as additive and uncorrelated. The probability distribution for the photon multiplication gain noise depends on the type of the detectors used which is neither Poisson nor Gaussian. Nevertheless, people often model the overall noise as a Gaussian random variable of the same mean and variance to get a rough estimate of the measurement precision.

A lidar has to first correctly detect the target return from noise in order to make a valid measurement. There are many techniques for target detection, most of them inherited from the radar theory. The received signal is first low-pass filtered to give the best SNR. The optimal low-pass filter for laser pulse detection is difficult to derive because of the complexity of the noise distribution and the multiplicative nature of the shot noise and the photoelectron multiplication noise. The matched filters derived from radio frequency (RF) communication and radar theory are often used (Skolnik, 2001). Since the received pulse width is not known, a bank of matched filters are often used and the receiver decides which output to use based on its SNR.

A range gate is often set based on the predicted target range to limit the length of the search window to minimize the probability of false detection. The simplest method to find the target return is to compare the signal with a predetermined threshold and designate the first threshold crossing as the target return. The detection threshold has to be sufficiently high in order to keep the false detection rate below an acceptable level. The detection threshold can be dynamically adjusted to keep the noise event rates at the acceptable level while maximize the probability of detection. The actual noise event rate can be monitored by the rate of threshold crossings in between the laser shots, which then can be used as the feedback to the threshold adjusting algorithm. As an example, Fig. 5 shows the block diagram of the Mars Orbiter Laser Altimeter (MOLA) (Abshire et al., 2000) which was launched in 1999 and successfully mapped the surface elevation of Mars. MOLA used simple rising edge threshold crossing detection. It had four matched filters of different impulse response, and each channel had its own automatic threshold adjusting algorithms. The matched filters were designed to optimize SNR from 3 to 30 degree sloped surfaces. The first matched filter output that exceeds the threshold was chosen as the ground return. Each receiver channel also measured the pulse width and the energy (pulse area) between the threshold crossings at the pulse rising and falling edges.

The receiver SNR needs to be sufficiently high in order to make a reliable detection. For single-pulse threshold crossing detection, the average received pulse amplitude has to be greater than five times the standard deviation of the background noise, or \(SNR_0 \geq 5\), in order to achieve a 90% probability of detection and <5% false detection rate over a few kilometer range gate window.

Another detection method is the peak detection in which the maximum signal amplitude is detected with a predetermined threshold and designated as the target return. The peak detection technique is more sensitive and can give a reliable detection with \(SNR_0 \geq 3\). The most sensitive detection technique is to record all the received signals and search for cohesive ground returns over a number of consecutive measurements. Surface returns form a continuous topographic profile, cloud returns form clusters, and false detection due to noise are uniformly distributed within the range gate window. Peak detection requires the receiver to record the time series of received signal over the range gate window which is readily achievable with today’s technology. Once the signal waveform is digitized and recorded, the matched filters, peak detection, and target characterization can all be performed using digital signal-processing (DSP) techniques with well-established DSP electronics and software.

Once the surface returns have been correctly identified, one can determine surface elevation from the laser pulse time-of-flight, surface slope from pulse width, and surface reflectance from the ratio of the received to the transmitted laser pulse energies and the range.

The measurement precision of the received laser pulse energy is the same as the SNR (Gardner, 1982, 1992), as

$$\epsilon_{E_r} = \frac{\langle E_r \rangle}{\sigma_{E_r}} = SNR_1$$

where \(\epsilon_{E_r}\) is the relative error of the pulse energy measurement, \(\langle E_r \rangle\) and \(\sigma_{E_r}\) are the mean and the standard deviation of the measured, and \(SNR_1\) is given in Eq. (5). Here we have assumed that the transmitted laser pulse energy is known or at least can be estimated with a much higher SNR and greater precision.
The measurement precision of the laser pulse time-of-flight is given by (Gardner, 1982, 1992)

\[ \sigma_R^2 = \frac{c^2}{2} \sigma_{\text{tof}}^2 + \frac{c^2}{2} \sigma_{\text{clk}}^2 + \sigma_{R\phi}^2 \]  

(8)

where \( \sigma_R \) is the standard deviation of total range measurement error; \( c \) is the speed of light; and \( \sigma_{\text{tof}}, \sigma_{\text{clk}}, \sigma_{R\phi} \) are the standard deviations of the time-of-flight, clock time, and range error due to the uncertainties in the laser beam pointing angle determination.

The time-of-flight of the laser pulse is the first-order temporal moment, or the centroid, of the received pulse waveform (Gardner, 1982, 1992). Assuming a Gaussian like pulse waveform, the measurement error can be approximated as

\[ \sigma_{\text{tof}}^2 = \frac{w_p^2}{\text{SNR}} \]  

(9)

where \( w_p \) is the root-mean-square (rms) pulse width, or the second temporal moment of the received pulse. The received pulse width can be approximated by the root-sum-square (RSS) of the laser pulse widths and the target impulse response. The latter is a function of the surface slope and the laser incident angle. The received laser pulse width is about the same as the transmitted laser pulse for nearly flat surface but increase almost linearly with the surface slope for large sloped surface. The laser beam incident angle has the same effect as the surface slope. Based on Eq. (9), there is an advantage to use a short pulse laser and keep the laser beam pointed in the nadir direction for a surface elevation lidar.

The time-of-light of the laser pulse can also be determined by curve fitting of the received data a known pulse shape function. If the transmitted laser pulses can be approximated to have a Gaussian pulse shape, the received pulse from a flat or sloped surface should also have a Gaussian pulse shape but with a different amplitude, width, and delay time. One can solve for these parameters through the curve fitting. The time-of-flight is the relative delay time between the centers of transmitted and the received pulses. Curve fitting generally gives a more precise and robust estimate since it uses all the information in the received waveform data, not just the rising and falling edges of the pulses. The fitting algorithm is similar to a matched filter which ensures the highest SNR but requires prior knowledge of the received pulse shape. It is more involved to calculate the rms error of the time-of-light with curve fitting, but Eq. (9) can often be used as an approximation.

The measurement error of the time-of-flight with threshold crossing detection is usually a few times larger than that with curve fitting. The error is roughly equal to the pulse rise time divided by the receiver SNR at the time of the threshold crossing. The SNR in this case is a function of time and difficult to calculate due to the multiplicative nature of the photodetector noise. Details about how to calculate the time-of-flight measurement error for threshold crossing detection can be found in Abshire et al. (2000).

**Fig. 5** Block diagram of the MOLA receiver (Abshire et al., 2000).
The clock timing error is given by

\[ \sigma_{\text{clk}} = \left( \frac{\sigma_{\tau}}{f_{\text{clk}}} \right) \]

where \( \langle T_{\tau} \rangle \) is the average time-of-flight of the laser pulse, \( \sigma_{\tau} \) is the standard deviation of the clock frequency including the frequency drift and timing jitter, and \( f_{\text{clk}} \) is the average clock frequency. The average clock frequency has to be periodically calibrated in orbit since the frequency drifts overtime. The clock oscillator has to be sufficiently stable so that the frequency drift in between the calibrations can be precisely estimated. The clock time error depends on the quality of the clock oscillator and the random timing jitter of the electronics. The clock stability is usually measured by the normalized Allan Deviation, which is defined as the standard deviation of the frequency difference between two successive gate intervals divided by the nominal clock frequency (Allan et al., 1974). The clock oscillator on a lidar receiver should have a sufficiently high stability so that the clock timing error is negligible in the total ranging error budget. For example, if a lidar is required to achieve 1-cm measurement accuracy from a 600-km altitude, the clock frequency has to be known better than 1 cm/600 km, or \( \lesssim 1.6 \times 10^{-8} \). To keep the clock timing error to 1/10 the total ranging error budget, a clock oscillator stability of \( \lesssim 1.6 \times 10^{-8} \) is needed in both short-term timing jitter and mid- to long-term drift. The short-term time period to consider is the average laser pulse time-of-flight. The mid- to long-term time period to consider is the time between the clock calibrations. As an example, if we assume the lidar can calibrate its clock frequency with the on-board GPS receiver every 1000 s, we need a clock oscillator with normalized Allan Deviation about \( 1 \times 10^{-9} \) (1 part per billion, or 1 ppb) from 0.004 to 1000 s gate time. The GPS 1 pps ticks used to calibrate the clock frequency needs to be better than 1 µs so that the clock oscillator frequency can be calibrated to \( 1 \times 10^{-9} \) over a 1000-s period. It usually requires an oven controlled crystal oscillator (OCXO) to achieve such stability. The frequency of a clock oscillator also varies with temperature and power supply voltage, which need to be regulated or modeled so that the residual clock frequency change is within \( 1 \times 10^{-9} \).

The ranging error due to laser beam pointing uncertainty on sloped surface can be calculated based on the geometry shown in Fig. 3, as (Gardner, 1982)

\[ \sigma_{\text{range}} = \frac{\tan(\theta_{\text{slope}} + \phi_m)}{\cos(\theta_{\text{slope}} + \phi_m)} \langle R \rangle \sigma_{\phi} \]  

where \( \theta_{\text{slope}} \) is the surface slope, \( \phi_m \) is the laser pointing angle in the direction of the surface slope, \( \langle R \rangle \) is the average spacecraft altitude, and \( \sigma_{\phi} \) is the standard deviation of the laser beam pointing uncertainty. The ranging error due to laser beam pointing and the surface slope is usually much greater than the time-of-flight measurement error and the clock timing error. The laser beam pointing error usually varies relatively slowly and affects mostly the long baseline surface elevation profile. The local topography measurement precision is mostly limited by the time-of-flight measurement error and the clock timing error. There are several methods to reduce the effect of the laser beam pointing uncertainty. One method is to periodically estimate the laser pointing bias from conical ocean surface scans (Luthcke et al., 2005). Another method is to solve for a slow varying pointing bias by minimizing the ranging discrepancies at the intersections of two intersecting ground tracks, also known as cross-over analysis (Neumann et al., 2001).

### 1.15.2.3 History of Surface Elevation Lidar

The first space-based lidar sensor was a laser ranger developed by the United States on the Apollo 15–17 missions in the early 1970s using a flash lamp-pumped ruby laser at 3.75 pulses per minute (Sjogren and Woffenhaupt, 1973). The advent of diode-pumped solid-state lasers in the late 1980s made it possible for space lidar to operate continuously in a multiyear mission. The first space-based lidar that used a diode pumped Nd: YAG laser was the YAG laser was the Mars Orbiter Laser Altimeter (MOLA) developed at the National Aeronautic and Space Administration (NASA) Goddard Space Flight Center (GSFC) on the Mars Observer mission in Zuber et al. (1992). Unfortunately, the spacecraft had a problem in its fuel system and did not reach the Mars orbit. A smaller laser ranger with similar laser and detector developed by the Naval Research Lab flew on the Clementine mission to the Moon in 1994 and provided a global topographic map of the entire lunar surface at a few hundred-meter precisions (Zuber et al., 1992; Smith et al., 1997). A small laser ranger developed by the Johns Hopkins University Applied Physics Laboratory on board the Near Earth Asteroid Rendezvous (NEAR) mission. It was launched in 1994 and successfully measured the topography and shape of the near Earth asteroid 433 Eros (Zuber et al., 1994). A second MOLA was built by NASA GSFC and launched in 1999 on-board Mars Global Surveyor (MGS) mission (Zuber et al., 1998). MOLA was a major milestone in planetary lidar sensor. It mapped a major planet of the solar system with about 650 million Mars surface elevation measurements over a full Martian year (Cavanaugh et al., 2007; Sun and Neumann, 2015). MLA was similar to MOLA in functionality and performance but \( \frac{1}{4} \) the size and mass. It also had to operate under harsh thermal environment in Mercury orbit. MLA successfully mapped the surface elevation, reflectance, and global shape of Mercury northern hemisphere, including permanently shadowed regions in polar regions where the cameras could not observe
MLA has achieved the longest ranging distance, about 1500 km, high slant angle ranging (Sun et al., 2012), planetary fly-bys measurement (Zuber et al., 2008), and simultaneous laser ranging and active surface reflectance measurements (Neumann et al., 2013).

Several laser altimeters have flown in lunar orbit in recent years. These include the laser altimeter (LALT) on the Japanese lunar explorer Selenological and Engineering Explorer (SELENE or Kaguya) launched in 2007 (Araki et al., 2008, 2009, 2013), the laser altimeter on the Chang’E-1 spacecraft launched in 2007 (Sun et al., 2005; Ping et al., 2009), and the Lunar Laser Ranging Instrument (LLRI) on the Chandrayaan spacecraft launched in 2008 (Kamalakar et al., 2005, 2009; Bhaskar, 2011). All three lidar sensors successfully mapped the lunar surface elevation, each with about 10 million laser altimetric measurements. The Lunar Orbiter Laser Altimeter (LOLA) developed at NASA GSFC was launched June 2009 on board the Lunar Reconnaissance Orbiter (LRO) (Smith et al., 2010a,b; Zuber et al., 2012b). LOLA is the first multibeam laser altimeter in space. A diffractive optical element (DOE) was mounted on top of the laser beam collimating telescope (beam expander) that splits the laser into five beams in slightly different directions. There are five independent receiver channels, each looking at one laser spot on ground. LOLA is still operating to this date and has made almost 7 billion lunar topographic measurements of the Moon. LOLA provided a high precision surface albedo map with the laser (Lucey, 2014) and surface reflectance to the sunlight from the noise of the photodetector output in between the laser pulse detections (Barker et al., 2015). The surface albedo data from lidar sensors are unique because it provided continuous measurement daytime and nighttime under uniform illumination and observation angle, including the permanently shadowed regions in polar region. The surface reflectance from the laser measurement (active) at zero phase angle and that from the sunlight (passive) at different phase angle complemented each other to provide additional information about the lunar surface. The measurements were through a narrow spectral band and had precise geolocation as the altimetric measurements (Sun et al., 2006; Barker et al., 2015). Fig. 7 shows the LOLA data products, the surface elevation, slope, roughness, and the albedo. A summary of the four space lidars developed at NASA GSFC can be found in Sun et al. (2013).

Lidar sensors for Earth surface elevation were developed about the same time as the planetary lidar sensors. A special challenge for Earth-orbiting lidar sensors is that they have to have comparable measurement precision and accuracy as the ground based instruments, but under the constraint of size, mass, and electrical power of nowadays spacecrafts. Airborne experiments were usually conducted to validate the technologies and numerous space missions were proposed (Bufton, 1989; Bufton et al., 1991). Space Shuttles and International Space Station were also used to validate the lidar technology. For example, the Airborne Topographic Mapper (ATM) lidar sensor was first used to demonstrate laser altimetry over ice on Greenland. It has later been used to routinely to survey coastal areas, ice sheet, etc. (Brock et al., 2002). The Laser Vegetation Imaging Sensor (LVIS) (Blair et al., 1999) has been developed in the late 1990s to validate the lidar sensor for biomass inventory. It has now been used routinely to survey vegetation, land, and ice and snow surface in many parts of the world. A pathfinder surface elevation lidar sensor was flown on the Space Shuttle.
Transportation Systems (STS), or Space Shutttles, in 1996 and 1997 (Garvin et al., 1998). All of these led to the first Earth-orbiting lidar, GLAS on ICESat launched in 2003 (Zwally et al., 2002; Schutz et al., 2005; Abshire, 2005; Wang et al., 2011). GLAS had one surface altimetry channel at 1064 nm wavelength and two cloud and aerosol backscattering profile channels at 1064 and 532 nm, respectively. ICESat completed its science mission in 2009 with about 2 billion laser shot measurements at 2–3 cm surface elevation precision, providing an unprecedented data set of ice sheets in Antarctica and Greenland, sea ice in the Arctic, land and vegetation in mid-latitude, and atmosphere back scattering profiles across the globe.

1.15.2.4 Future Surface Elevation Lidar and the Trend of the Technology Developments

There are two planetary surface elevation lidars currently being built, the Bepi-Colombo Laser Altimeter (BELA) on the Bepi-Colombo mission by the European Space Agency (ESA) to be launched in 2018 (Thomas et al., 2007; ESA, 2017a) and the Ganymede Laser Altimeter (GALA) on the Jupiter Icy Moon Explorer (JUICE) mission by ESA to be launched in 2022 (Lingenauber et al., 2014; ESA, 2017b). These are single-beam lidars, but BELA has to operate in an even more severe thermal environment than MLA, and GALA has to survive the much harsher radiation environment in the Jovian system.

There are two Earth-orbiting surface elevation lidars currently being built. These are the Advanced Topographic Laser Altimeter System (ATLAS) on the ICESat-2 mission by NASA GSFC to be launched in 2018 (Abdalati et al., 2010; NASA, 2017) and the Global Ecosystem Dynamics Investigation (GEDI) lidar by NASA GSFC to fly on the International Space Station (ISS) in 2019 (NASA, 2016). ATLAS has six laser beams which will provide much denser surface elevation coverage and will be able to measure the surface slope across the ground tracks. It uses high pulse rate lasers and single-photon detection at 532 nm wavelength, which improves the receiver sensitivity and finer spatial resolution along the ground tracks. GEDI is a special type of surface elevation lidar that is optimized to measure vertical profiles of vegetation above ground to provide the first high-resolution measurement of the 3-D structure of the Earth’s tropical and temperate forests for carbon cycle and biodiversity studies. GEDI will have three lasers into 10 beams to sample the Earth surface in mid-latitude which covers nearly all tropical and temperate forest area on Earth.

Future surface elevation lidars are moving toward multibeams and consecutive footprints swath mapping or 3-D imaging measurement. The number of beams increases to improve the coverage, while the laser footprint size decreases to improve the spatial resolution. LOLA is the first multiple beam surface lidar in space which has demonstrated its advantage in simultaneous surface slope and roughness measurement. Multibeam lidar also provides many times more cross-overs points to help solving for laser beam pointing angle. NASA has been developing the Lidar Surface Topography (LIST) as the next-generation surface elevation lidar. LIST is required to have a 5-m diameter laser footprint size and up to 1000 beams (5 km swath) to map the entire Earth surface in 2–3 year. LIST is going to map lands, ice sheet, and vegetation coverage, just like ICESat and GEDI, but with smaller and contiguous laser footprints on ground. The major technology challenge for multiple beam swath mapping lidars is the measurement efficiency since LIST has to make many times more measurements but within the resource constraints of a typical Earth-orbiting spacecraft. The electrical to optical conversion efficiency of the laser transmitters has to be increased many folds. The detector has to have single-photon sensitivity and near quantum limited performance. The receiver also has to have a wide linear dynamic range and be able to measure the vertical profiles of vegetation and the ground surface under the trees. It is preferred to use pixelated detector and illuminate the scene with a single laser pulse, as in a flash lidar, instead of using a single channel lidar with a mechanical scanner to achieve the coverage. The measurements should be done at the fundamental laser wavelengths at near
infrared without having to convert the wavelength to the visible for the availability of the single-photon detectors. The detectors have to work at the near infrared wavelength and provide analog waveform outputs with a noise floor of much less than one phot-electron over the received laser pulse width. All of these technologies are available today though still need to be further developed to achieve the required technical readiness level (TRL) for space applications. An airborne LIST simulator has been developed which has one laser split into 16 beams and a 16-element single-photon detector array (Yu et al., 2012). Major challenges remain in size, mass, power, and cost, especially in the areas of high efficiency laser, large array size photon detector, and real-time data processing and storage.

1.15.3 Atmosphere Backscattering Lidars
1.15.3.1 Principle of Operation
Atmospheric backscattering lidars measure the attenuated atmospheric backscatter coefficient as a function of altitude (Measures, 1984; Kovalev and Eichinger, 2004; Weit Kamp, 2005). The targets in this case are air molecules as well as suspended particulate matter in a volume along the laser beam path. The backscattered signals start when the laser pulse hits the upper atmosphere and end when it reaches the ground. The receivers record the signal over the entire time period. The amplitude of the received signal is proportional to the backscattering coefficient (cross section) of the atmosphere at a given altitude attenuated by the atmosphere between that altitude and the lidar. The signal waveform gives a continuous profile of the attenuated backscatter versus distance or altitude. The signal is usually weak, so a relatively long averaging time is required to reach a useful SNR. Fig. 8 shows an example of the backscattered signal from ICESat/GLAS 532-nm wavelength atmosphere backscattering channel. As the spacecraft orbiting around Earth, the lidar can provide a continuous measurement of the vertical profile of the atmosphere along the ground track, as shown in Fig. 9, a sample ICESat/GLAS 1064 and 532 nm atmosphere backscattering measurement for a full orbit around Earth.

There are several types of atmosphere backscattering lidars, depending on the laser wavelength selection and the receiver configuration (Measures, 1984). Rayleigh and Mie backscatter lidars measure the elastic backscattering of the molecules and particles in the atmosphere, in which the received laser signal wavelength is exactly the same as the transmitted ones (Kovalev and Eichinger, 2004). The measurement data can be used to infer the molecule and particle density when the backscattering cross sections of individual molecule and particles are known and the effect of multiple scattering can be neglected. There is no particular requirement for the laser wavelength as long as the backscattering cross sections are high. The lidar measurement data provide key observations to validate the atmosphere model. Measurements at multiple wavelengths are highly desired to give additional information about the scatters and their composition. Polarization can also be used to give additional information about the atmosphere composition, such as the cloud ice water content.

Raman backscatter lidars are similar to Rayleigh and Mie backscattering lidars but measure the return signals at the Raman-shifted wavelength. The exact wavelength depends on the targeted molecules and their excitation energy to produce Raman-shifted backscattering. The receivers have to have a spectral filter that is centered to the Raman-shifted signal and block out the transmitted laser wavelength and background illumination noise. Raman lidars can be used to target a certain constituents and its vertical profile in the atmosphere, such as water vapor, with little interference from other molecules and particles in the atmosphere (Whiteman et al., 1992). Raman lidars are more difficult to built in general because the laser transmitter has to be at the exact wavelength and the receiver has to be able to filter out the Raman-shifted signal. The backscatter signal is usually weak and requires a relatively high-energy laser and long integration time.

Fig. 8 Sample atmosphere backscattering signal from ICESat/GLAS 532-nm channel.
Wind lidars are a type of atmosphere elastic backscattering lidars that measure the Doppler shift of the backscattered laser signal (Baker et al., 1995). The laser line width and the spectral stability need to be much narrower than the amount of Doppler shift to be resolved. The receivers measure the difference of the wavelengths between the transmitted and the received laser signal. The Doppler measurement corresponds to the component of the wind vector along the laser beam pointing direction. Coherent detection can be used, in which the received signal is combined with the transmitted laser to generate a beat note at the photodetector output. An electrical filter is used to filter out the Doppler-shifted signal (Huffaker and Hardesty, 1996). The beat signal is proportional to the electromagnetic field of the received signal but in RF frequency, which can be filtered out at a much finer resolution than that of an optical band pass filter. The major challenge for coherent lidar is to match the received and the transmitted laser (local oscillator) in both temporal and spatial modes to maintain a reasonably high coherent mixing efficiency. Another coherent wind lidar technique is the optical autocorrelation in which the received optical signal is correlated with a delayed version of itself in a Michelson interferometer configuration (Schwiesow and Mayor, 1995; Schwiesow, 2008). It is relatively easier to implement than a conventional coherent lidar since there is no need for a local oscillator laser.

A more widely used technique for wind lidars is the edge technique (Gentry and Korb, 1994), in which the received signal is split into two and filtered by two narrow band Fabry–Perot etalon optical interference filters. The center wavelengths of the two filters are slightly offset from the laser wavelength, one to the shorter and the other to the longer wavelength, as shown in Fig. 10. The ratio of the difference to the sum of the two signals from the two filter outputs is proportional to the Doppler shift of the received signal. Edge technique wind lidars use direction detection and are relatively easy to build and align than coherent wind lidars. Wind measurements usually require high special and temporal resolutions which limit the signal averaging time at the receiver. As a result, wind lidars require high power and narrow spectral line width lasers. It is generally preferred to use shorter-wavelength lasers, especially for measuring high-altitude wind which relies on the molecular backscattering. Longer-wavelength laser may be used for low-altitude wind measurement where aerosols are the dominant backscatters with a reasonably large backscattering cross section at the laser wavelength.

Another commonly used type of atmosphere backscattering lidars are the differential absorption lidar (DIAL) in which two lasers are used, one on a spectral absorption line of the targeted atmosphere specie and one at a near-by wavelength but off the absorption line (Measures, 1984). The receivers take the ratio of the atmosphere backscattering profiles online and offline of the absorption wavelengths to obtain the backscattering profiles of the target species of the atmosphere. DIAL is a powerful lidar measurement technique which can target a particular specie in the atmosphere and null out all other backscattered laser light and solar background illumination. The laser transmitters in this case have to have narrow line width and a stable center wavelength precisely at the absorption line of the target species. A closed-loop laser frequency locking system is usually required.
There are other types of atmosphere backscattering lidar sensors based on similar principles. One example is the sodium lidar used to observe high-altitude mesopause region winds and temperature (Bowman et al., 1969; She et al., 2003; Clemesha et al., 2011). The laser wavelength in this case is tuned to a resonant frequency of sodium atoms and causes them to resonate and reemit almost instantaneously, just like backscattering. The equivalent backscattering section is several orders of magnitude higher than ordinary Rayleigh backscattering, which makes it possible to detect a very thin layer of sodium at 80–100 km altitude even though it is a minor constituent.

1.15.3.2 Measurement Precision and Accuracy

Atmosphere backscattering lidars measure the backscattered signal amplitude as a function of time which can be converted to altitude. They have to have a high SNR in the signal amplitude but a less stringent requirement in the laser pulse time-of-flight and laser beam pointing determination. The received optical power is given by the lidar link equation (Measures, 1984)

\[ P_{\text{sig}}(l_r, t_l) = \frac{c}{2} E_{\text{tx}}(l_l) \cdot A_r \cdot \eta_R(l_r) \cdot \beta[l_r, l_l, R(t_l)] \cdot T_a[l_l, R(t_l)] \cdot T_a[l_l, R(t_l)] \]

where \( P_{\text{sig}}(l_r, t_l) \) is the received optical signal power at the receiver wavelength \( l_r \) from the volume scattering target at distance (range) \( R(t_l) = c t_l / 2 \) with \( c \) the speed of light and \( t_l \) the time since the laser pulse emission (time-of-flight), \( E_{\text{tx}}(l_l) \) is the transmitted laser pulse energy at wavelength \( l_l \), \( \eta_R(l_r) \) is the receiver optical transmission at the receiver wavelength, \( \beta[l_r, l_l, R(t_l)] \) is the backscattering cross section at the receiver wavelength in response to the laser wavelength at range \( R(t_l) \) in m\(^2\) per unit volume, or m\(^{-1}\), \( T_a[l_l, R(t_l)] \) is the one-way atmosphere transmission from the spacecraft to target at the laser wavelength and range \( R(t_l) \) and \( T_a[l_l, R(t_l)] \) is the one-way atmosphere transmission from the target back to the spacecraft at the receiver wavelength. It is assumed that the laser pulse width is much shorter than the vertical resolution of the atmospheric profile to be measured. It is also assumed that the receiver FOV is larger than the laser beam divergence angle that the entire laser beam is within the receiver FOV over the entire light path through the atmosphere. For Rayleigh and Mie backscattering lidars, the wavelength of the received signal is the same as the transmitted one, i.e., \( l_l = l_r \). For Raman backscattering lidars, the received wavelength is Raman shifted. A more detailed link equation of atmosphere backscattering lidar can be found in Measures (1984), Kovalev and Eichinger (2004), and WeitKamp (2005).

Photon-counting detectors are usually used for atmosphere backscattering lidars because the signals are much weaker compared to surface elevation lidars. The signal has to be first averaged over a time period which corresponds to a layer of atmosphere of certain thickness. The mean and standard deviation of the received signal can still be calculated using Eqs. (2)–(4), but replacing the received signal by

\[ E_r(l_r, t_l) = P_{\text{sig}}(l_r, t_l) \tau_{\Delta R} \]

with \( \tau_{\Delta R} = 2 \Delta R / c \) the receiver integration time for each laser shot corresponding to the thickness of atmosphere layer \( \Delta R \). The SNR can be calculated with Eq. (5b). Usually the SNR from a single laser pulse measurement is too low to be useful and the signal from a number of laser pulses has to be summed up before making a useful measurement. The SNR of the averaged signal increase as the
square root of the number of laser pulse measurements averaged. The spatial resolution of the lidar measurement is determined by the averaging time and the spacecraft velocity, which is about 7 km/s for a typical Earth-orbiting satellite.

The data from atmosphere backscattering lidars give the vertical profile of the atmosphere backscattering cross section and can be used to identify boundaries of clouds and aerosols. For example, one can take the derivative of the vertical profile to determine the height and thickness of clouds, the height of aerosol above the surface and ground fogs or blowing snows. The spatial extend of the clouds and aerosols can be obtained from horizontal profiles of cloud and aerosol layers from continuous measurement along the ground tracks of the satellites.

An atmosphere model is usually used in combination of the lidar measurements to determine the properties of the atmosphere because the lidar can only measure the apparent backscattering cross section at a given wavelength which is not sufficient to characterize the atmosphere. As an example, the atmosphere can be divided into layers. Each layer is homogenous with a constant backscattering cross function and transmission coefficient. The backscattering cross section in this case can be assumed as a constant within each layer, $\beta(\lambda, \omega) = \beta_s$. The optical transmission with the layer can be written according to the Beer–Lambert law (Measures, 1984), as

$$ T_{\lambda}[\lambda, R(t_1 - \tau_0)] = \exp \left( -\alpha_{\text{ext}}(\lambda) \frac{c(l_1 - \tau_0)}{2} \right) $$

where $\tau_0$ is the laser pulse time-of-flight when the laser just hits the cloud and $\alpha_{\text{ext}}(\lambda)$ is the atmosphere attenuation coefficient, which is often called extinction coefficient. The average receive signal energy for the atmosphere layer at $t_1$ can be written as,

$$ E_0(\lambda, t_1 - \tau_0) = N_{\text{shots}} \frac{E_{\text{in}}}{2} \frac{\lambda}{R(t_1)} \eta(\lambda) \beta_{\text{ext}} \exp \left( -2\alpha_{\text{ext}}(\lambda) \frac{c(l_1 - \tau_0)}{2} \right) $$

The atmosphere extinction coefficient can be solved by first correcting for the signal losses due to range, taking the logarithm, and then taking the derivative with respect to time, which is sometimes called the slope technique, as

$$ \frac{\partial}{\partial t_1} \left[ \ln[R^2(t_1) \cdot E(\lambda, t_1 - \tau_0)] \right] = -c \cdot \alpha_{\text{ext}}(\lambda) $$

In practice, the atmosphere is much more complicated and cannot be correctly described by the simplified model described earlier. Other factors have to be considered, such as the overlap between the laser beam and receiver field of view, especially for airborne and ground-based lidars. There are many species in atmosphere and each has a different cross section. There are generally more unknowns than the number of independent measurements. Forward modeling and a certain retrieving methods have to be used to obtain quantitative results. Multiwavelength measurements are highly desired.

The lidar equations for Raman lidars and resonance lidars are the same as those given in Eqs. (11) and (12) with the backscattering cross section being replaced by the appropriate backscattering cross section. The receivers have to have a narrow spectral filter to filter out the backscattered signal at the Raman-shifted wavelength, $\lambda_0 = \lambda_1 - \Delta\lambda_{\text{Raman}}$, but block elastic backscattering signals at the transmitted laser wavelength and other background light. The lidar equations for wind lidars are also the same as those given in Eqs. (11) and (12), but the receivers have to have even narrower spectral filters or other means to resolve the Doppler shift.

### 1.15.3.3 History of Atmosphere Backscattering Lidars

There is a long history of backscattering lidar sensors, which started soon after the invention of the lasers. It started with ground-based atmosphere backscattering lidars, airborne lidars, and spaceborne lidars. A summary of the airborne and spaceborne atmosphere backscattering lidars up to 2003 is given by McCormic (McCormick, 2005), including a description of the Lidar In-space Technology Experiment (LITE) by NASA’s Langley Research Center (LaRC) on aboard the Space Shuttle STS-64 in 1994. LITE was the first Earth-orbiting atmosphere backscattering lidar in space, and it orbited Earth for 9 days and collected atmospheric backscattering data at 355, 532, and 1064 nm laser wavelengths.

A summary of the wind lidar development can be found in Baker et al. (Baker et al., 2014). Technologies continue to evolve and the performance continues to improve for the ground-based and airborne atmosphere lidars over the years. Examples are the Cloud Physics Lidar (McGill et al., 2002; Hair et al., 2008) which measures the cloud and aerosol backscattering with different wavelengths and channels; the direct detection wind lidar by the European Space Agency (ESA) (Stoffelen et al., 2005); and the coherent airborne wind lidar by NASA LaRC (Koch et al., 2014).

There are several major DIAL atmosphere backscattering profile lidar developments. One example was the ozone DIAL lidars (Shumate et al., 1981; Browell et al., 1985; Megie et al., 1985; McGee et al., 1991; Sullivan et al., 2015). Another example was the atmosphere CO2 DIAL lidar (Kameyama et al., 2009). Most of this atmosphere backscattering DIALs are ground-based uplooking lidars because the laser power needed to achieve the required SNR of the signal from the relatively thin volume backscatters.

The GLAS instrument on ICESat was the first multi-year Earth-orbiting atmosphere backscattering lidar in space (Abshire, 2005; Kameyama et al., 2009) and operated from 2003 to 2009. GLAS was primarily a surface elevation lidar 1064 nm laser wavelength. It had a nonlinear crystal in the lasers that convert part of 1064 nm laser light into 532 nm. It had a set of single-photon counting detectors that detected the 532 nm atmosphere backscattering signal and binned the detected photons at 500 ns interval (75 m in range) for the entire 40 km atmosphere column. GLAS splits the 1064 nm detector output, one for surface elevation and the other for the atmosphere. The 1064-nm atmosphere channel output was low-pass filtered, sampled at 500 ns interval, and binned for the
40-km atmosphere column. To extend the mission duration, GLAS operated in three science measurement campaigns each year early in the mission and later reduced to two campaigns per year. The atmosphere channels had a minimum detectable backscattering section of $10^{-7}$ m$^{-1}$ at 532 nm and $10^{-6}$ m$^{-1}$ at 1064 nm early in the mission (Spinheimer et al., 2005) and decreased over-time as the laser pulse energy degraded. Fig. 9 showed a sample results from both of the GLAS atmosphere channels.

The Cloud–Aerosol Lidar with Orthogonal Polarization (CALIOP) on the Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite was launched in 2006 and still operates to this date. CALIOP was developed by NASA LaRC and Ball Aerospace & Technology Corporation (Winker et al., 2003, 2004, 2009; Hunt et al., 2009). CALIPSO measures the atmosphere backscattering profiles at 532 and 1064 nm. The 532-nm channel also has a polarizer that can be moved in and out of the 532-nm receiver path to provide backscatter measurement at both polarizations to provide vertical profile of atmosphere ice water content. CALIPSO was one of the seven Earth-observing satellites in the Afternoon Constellation, or A-Train satellites (Atrain, 2015) and provides concerted remote-sensing data with other satellites. CALIPSO lidar has been operating continuously since launch and accumulated more than 3 billion laser pulse measurements to date.

The Cloud–Aerosol Transport System (CATS) (NASA, 2015; Yorks et al., 2016) is the latest spaceborne atmosphere backscattering lidar. CATS was launched and installed on to the International Space Station (ISS) in January 2015. It has three channels at 355, 532, and 1064 nm wavelengths and uses single-photon detectors similar to those in GLAS. It has been operating continuously since launch except for brief periods during special ISS activities.

### 1.15.3.4 Future Atmosphere Backscattering Lidar and the Trend of the Technology Developments

There have been four space-based atmosphere backscattering lidars to date, LITE, GLAS, CALIOP, and CATS. The next in line to be launched is the ADM-Aeolus wind lidar for Earth by the European Space Agency (ESA) scheduled to launch in 2017 (Reitebuch et al., 2009; Reitebuch, 2012; ESA, 2013). The technologies in atmosphere backscattering lidars continue to evolve over the years. The lasers are still a major challenge because of the signals in this case are much weaker than those from other type of lidars. High-power laser transmitters are required in order to produce detectable signal. The new atmosphere lidars are moving beyond elastic backscattering lidar and target more specific constituents in the atmosphere, such as CO$_2$ and water vapor. The trend of the technology development is to improve the technology readiness level for space applications and reduce cost.

### 1.15.4 Laser Spectral Absorption Lidars

#### 1.15.4.1 Principle of Operation

Lidar sensors can be used to remotely probe a specific spectral absorption line of a certain atmosphere constituent or surface element, either sampling the line at discrete laser wavelengths or scanning across the line continuously. The lidar sensor becomes a laser absorption spectrometer with its own light source instead of sunlight. Compared to conventional spectrometers, laser spectral absorption lidars measure the surface element and/or atmosphere day and night under a uniform lighting condition. The data are also easier to interpret because there is no need for photometric correction due to sun angle, topography, etc. The spectral resolution of a laser spectral absorption lidar is determined by the laser wavelength stability and the line width, which can be much more precise and accurate than the resolution of passive spectrometers. The most commonly used laser spectral absorption lidars up to now are integrated path differential absorption (IPDA) lidars, in which the receiver measures the difference in the surface reflection at a certain atmospheric absorption line (online) and a nearby wavelength (offline), as depicted in Fig. 11, just like the DIAL atmosphere backscattering lidar but measuring the differential reflectance of the ground surface. Similarly, with the proper choice of the laser wavelengths, a laser absorption spectrometer lidar can also be used to measure the abundance certain elements on the surface but not the atmosphere column.

IPDA lidars are similar to surface elevation lidars but primarily measure the surface reflectance at multiple laser wavelengths. The received signal of an IPDA lidar is much stronger compared to atmosphere backscattering lidars, but it only measures the total column absorption instead of the vertical profile of the atmosphere constituent. The required SNR is usually high in order to resolve the changes in the abundance of the atmospheric species. For example, the SNR for a CO$_2$ IPDA lidar has to be $> 400$ in order to detect 1 part per million (ppm) changes out of 400 s CO$_2$ in the atmosphere. Most IPDA lidars use DIAL technique with the online and offline laser wavelength at the spectral absorption line being targeted. The laser transmitters can be continuous wave (CW) lasers with and without modulation. For direct detection IPDA lidars, a CW laser can be intensity modulated (chopped) and the receiver cross-correlates the received signal with the modulation signal, a technique commonly known as lock-in amplifier detection. The lock-in amplifier can detect very weak signal from a relatively strong background noise. A lock-in type IPDA lidar can have several lasers emitting simultaneously at different wavelengths. Each laser is modulated by a different frequency, detected with a common detector, but cross-correlated with different modulation signal (Pruitt et al., 2003). The laser can also be pulsed like in a surface elevation lidar with the laser output alternating between the online and offline wavelengths (Abshire et al., 2010). Coherent detection can also be used for IPDA lidar with either CW or pulsed lasers (Spiers et al., 2002; Koch et al., 2004; Pearson and Collier, 1999; Gibert et al., 2006). Fig. 12 shows a block diagram of laser transmitters for IPDA lidars. Fig. 13 shows block diagrams of the receivers for coherent detection, lock-in detection, and pulsed modulation and detection IPDA lidars (Sun and Abshire, 2012).
The major advantages of the coherent IPDA lidars are the high signal gain at the heterodyne or homodyne detection and narrow bandwidth. Coherent lidars can use ordinary photodiodes without internal photoelectron multiplication gain. The combined received signal multiplied by the local oscillator laser is usually sufficient to overcome the detector electronics noise. The signal output from the detector is proportional to the electromagnetic field of the received optical signal, but frequency downshifted to a RF frequency. One can use mature RF techniques to process the signal, such as Fast Fourier Transform (FFT), frequency and phase locks, and narrow band filtering. The major challenges for coherent IPDA lidars are spatial mode matching of the received and the local oscillator lasers and speckle noise. The receiver telescope size cannot exceed the coherent size of the speckles. The speckle size at the receiver is inversely proportional to the laser footprint size on the surface, which is limited by the size of the laser collimator.

The major advantages of lock-in type direct detection IPDA lidars are simultaneous online–offline laser illumination on the surface and low peak laser power requirement. The major disadvantages are the continued receiver integration time, susceptibility to background noise, and lower SNR compared to a pulsed direct detection IPDA lidar under the same average laser power (Sun and Abshire, 2012). A pulsed IPDA lidar provides not only the surface return but also the atmosphere backscattering profile. It integrates signal only about the laser pulse arrival time and gates out solar background noise and other spurious signals. It can readily identify clouds and aerosol and provide simultaneous range measurement, just like a surface elevation lidar. The major challenge for a pulse IPDA lidar is the requirement for high peak power of the laser transmitter.

The choice of the laser wavelengths directly affects the performance of the IPDA lidars. The offline laser wavelength should be close to the online laser wavelength so that the effects from other atmosphere constituents and instrument are nearly identical and can be canceled out when taking the ratio of the two in post signal processing. The offline wavelength has also been away from spectral absorption lines of any other constituents. On the other hand, the offline laser wavelengths should not be too far from the online laser wavelength so that they can pass a common narrow band optical filter to reduce the solar background light during daytime measurements. The signal levels at the offline laser wavelengths are stronger and have higher SNR. The signal at online wavelength has a lower SNR due to the absorption. The laser wavelength has to be precisely controlled via an automatically control loop in reference to the gas absorption line. Any offset and jitter in the laser wavelengths directly affect the lidar measurement precision and biases.

Another consideration in the laser wavelength selection for a DIAL IPDA lidar is the weighting function that the total column atmosphere gas molecule density is integrated from that of each atmosphere layer. The measurement at the peak absorption has more weight on the atmosphere molecule density at high altitude while the primary interest is often in the changes of molecule density at lower altitude. The online laser wavelength is sometimes placed on the side of the absorption line where the measurement is more sensitive to the line broadening by the pressure and water vapor and has more weight on the atmosphere at lower altitude.
More than two laser wavelengths can be used in DIAL IPDA lidars to provide additional information about the atmosphere species being measured and help to reduce the measurement biases. For example, the Multifunctional Fiber Laser Lidar (MFLL) has two offline laser wavelengths, one on each side of the CO$_2$ absorption line at 1571.061 nm, to calibrate out potential variation in the receiver optical transmission and gain versus wavelength and to improve the of measurement SNR (Dobler, 2013). The 2-μm triple-pulsed IPDA lidar uses three laser wavelengths to simultaneously measure CO$_2$ and H$_2$O (Refaat et al., 2015). Multiwavelength sampling of an absorption line can also be used in IPDA lidar, which gives the line shape besides the total column absorption (Ben-David et al., 1992). The data from a multiwavelength sampling IPDA lidar can be used to estimate the Doppler shift and line broadening via curve fitting (Ben-David et al., 1992; Chen et al., 2014). It significantly reduces the effects of instrument artifacts, such as laser wavelength jitter and uneven receiver optics transmission. Multiwavelength sampling is not necessarily the more efficient methods in terms of measurement precision versus average laser power because the wavelength samples are placed across the entire absorption line instead of where it gives the highest receiver SNR. Nevertheless, it provides means to control measurement biases and additional information about absorption line shape.

1.15.4.2 Measurement Precision and Accuracy

Laser spectral absorption lidars measure the reflected or backscattered laser pulse energy and monitor the transmitted laser pulse energy to a great precision to take the ratio the two. They also have to measure the distance from the satellite to the surface, either from the laser pulse time-of-flight in the case of a pulsed IPDA lidar, or rely on other means, such as a Global Positioning System (GPS) receiver, to determine the height of the atmosphere column in order to normalize the received signal to obtain the column

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**Fig. 13** Block diagrams of IPDA lidar receiver for: (A) coherent detection, (B) direct detection with sine-wave laser intensity modulation and lock-in type detection, and (C) direct detection with pulsed modulation and detection (Sun and Abshire, 2012).
density of the molecules being measured. An atmosphere model has to be assumed in order to retrieve column density of the atmosphere species to be measured, since lidars can only measure a few parameters while the atmosphere is far more complicated than a few parameters can describe. A line shape function is usually required based on the theoretical model and metrological data from ground based sensors and other Earth-monitoring satellites. The lidar measurements can be used to determine the depth of the absorption and hence the density of the atmosphere molecules being targeted. A least square error method can be used to fit the measurement data to the line shape function to best estimate the parameters of interest. More details about the retrieval of the atmosphere parameters from sample measurements and models can be found in Rodgers (2000).

The measurement precision of an IPDA lidar can be analyzed as follows. A pulsed multiwavelength sampling CO2 IPDA lidar at 1572.33 nm is used as an example. The result can also be applied to the two-wavelength DIAL IPDA lidar by reducing the number of wavelength samples to just online and offline wavelengths.

Assuming the IPDA lidar transmit laser pulses at successive wavelengths across the CO2 absorption line, as shown in Fig. 14. The received signal at each laser wavelength can be written as

$$S(\lambda_i) = S_{\text{total}}(\lambda_i) - S_{\text{bg}} = C_{\text{sys}} \cdot \rho_{\text{sur}} \cdot T_{\text{atm}}^2(\lambda_i)$$  

(15)

where $\lambda_i$, $i = 0 \ldots N_2 - 1$, is the laser wavelength used to sample the CO2 absorption line, $S_{\text{bg}}$ is the background light, $C_{\text{sys}}$ is a system constant, $\rho_{\text{sur}}$ is the surface reflectance, and $T_{\text{atm}}(\lambda)$ is the one-way atmosphere optical transmission at the sampling wavelength. Based on the Beer–Lambert law (Measures, 1984), the atmosphere transmission can be written as

$$T_{\text{atm}}(\lambda) = \exp\left\{ -[OD_{CO2}(\lambda) + OD_{\text{offline}}]\right\} = \exp\left\{ -[a_{CO2} \cdot OD_0(\lambda) + OD_{\text{offline}}]\right\}$$  

(16)

where $OD_{CO2}(\lambda)$ is the total column optical depth of the atmosphere at a given wavelength, $OD_{\text{offline}}$ is the optical depth at the offline laser wavelength, $a_{CO2}$ is a scale factor for the line shape function, and $OD_0(\lambda)$ is the precalculated line shape function. Our objective is to solve for this scale factor via curve fitting using a least squares error method. Other parameters, such as the Doppler shift and the amount of line broadening, may also be obtained from curve fit. Here we consider only the scale factor, which is proportional to the number of CO2 molecules and hence the CO2 mixing ratio in the atmosphere column.

It becomes a linear least square fit when fitting the optical depth line shape function to the logarithm of the measurement data, as shown in Fig. 15. The choice of the sampling laser wavelengths also affects the measurement precision, as mentioned earlier. The scale factor for the optical depth line shape function is the slope of the fitted line. The points at larger optical depths have more leverage in determining the slope of the line, but they also have lower SNR due to the CO2 absorption. It can be shown that the optimal points of the online laser wavelengths should be near unity optical depth. In practice, other factors have to be considered, such as bias control, sensitivity to environmental and instrument variations, etc. For simplicity, we place the wavelength samples at roughly equal step in the optical depth. Eq. (15) can now be rewritten as

$$\ln[S(\lambda_i)] = -2[a_{CO2} \cdot OD_0(\lambda_i) + OD_{\text{offline}}] + \ln[\rho_{\text{sur}}] + \ln[C_{\text{sys}}]$$

$$= -a_{CO2} \cdot [2 \cdot OD_0(\lambda_i)] - b$$  

(17)

where $b$ is an offset which combines the effects of the offline atmosphere transmission, surface reflectance, and system parameters. The sum of the squares of the misfit between the data and the line shape function, also known as the loss function, can be written as

$$\epsilon(a_{CO2}, b) = \sum_{i=0}^{N_2-1} w_i \left[ \ln[S(\lambda_i)] + a_{CO2} \cdot [2 \cdot OD_0(\lambda_i)] + b \right]^2$$  

(18)

**Fig. 14** Example of multiwavelength sampling across the 1.57233 μm CO2 absorption line used by a pulsed IPDA lidar (Chen et al., 2014). The error bars are equal to 1/SNR, which changes with the atmosphere transmission.
where \( w \)s are weighting factors assigned to each error term. The use of the weighting factors allows us to balance out the contributions of each term in the above equation so that terms with high SNR weigh more in the curve fitting (Rodgers, 2000). The least square curve fitting method chooses \( \hat{a}_{CO_2} \) and \( b \) that minimize the loss function, which can be solved from the two linear equations,

\[
\begin{align*}
\frac{\partial \epsilon(a_{CO_2}, b)}{\partial a_{CO_2}} &= 0 \\
\frac{\partial \epsilon(a_{CO_2}, b)}{\partial b} &= 0
\end{align*}
\]

which yields

\[
\hat{a}_{CO_2} = \frac{1}{2} \left( \sum_{i=0}^{N-1} w_i [\text{ln}(S(\lambda_i))] \left\{ \text{OD}_0(\lambda_i) - \frac{1}{\sum_{i=0}^{N-1} w_i} \sum_{i=0}^{N-1} w_i \text{OD}_0(\lambda_i) \right\} \right)
\]

\[
\hat{b} = \frac{1}{2} \left( \sum_{i=0}^{N-1} w_i [\text{OD}_0(\lambda_i)]^2 - \frac{1}{\sum_{i=0}^{N-1} w_i} \sum_{i=0}^{N-1} w_i \text{OD}_0(\lambda_i)^2 \right)
\]

The mean and variance of the measurement data can be expressed as,

\[
\langle \text{ln}[S(\lambda_i)] \rangle = -\hat{a}_{CO_2} + [2 \cdot \text{OD}_1(\lambda)] - b
\]

and

\[
\text{var} \{ \text{ln}[S(\lambda_i)] \} = \text{var} \left\{ \frac{1}{\langle S(\lambda_i) \rangle} \hat{S}(\lambda_i) \right\} = \frac{1}{\langle \text{SNR}_i(\lambda_i)^2 \rangle}
\]

where \( \text{OD}_1(\lambda) \) is the actual line shape function that govern the signal and \( \text{SNR}_i(\lambda_i) \) is the signal to noise ratio at wavelength \( \lambda_i \). The mean and variance of the estimated scale factor can be derived from Eqs. (20)–(22), as,

\[
\langle \hat{a}_{CO_2} \rangle = a_{CO_2} - \frac{1}{2} \left( \sum_{i=0}^{N-1} w_i [\text{OD}_1(\lambda_i)] \left\{ \text{OD}_0(\lambda_i) - \frac{1}{\sum_{i=0}^{N-1} w_i} \sum_{i=0}^{N-1} w_i \text{OD}_0(\lambda_i) \right\} \right)
\]

\[
\text{var} \{ \hat{a}_{CO_2} \} = \frac{1}{4} \left( \sum_{i=0}^{N-1} w_i [\text{OD}_1(\lambda_i)]^2 - \frac{1}{\sum_{i=0}^{N-1} w_i} \sum_{i=0}^{N-1} w_i \text{OD}_0(\lambda_i)^2 \right) \left\{ \frac{1}{\langle \text{SNR}(\lambda_i)^2 \rangle} \right\}^2
\]

The optimal weighting factors for linear least square fit with Gaussian distributed noises are equal to the reciprocals of the variance of the measurement data (Bevington, 1969).
\[ w_i = \frac{1}{\text{var} \left[ \ln \left( S \left( \lambda_i \right) \right) \right]} \text{SNR} \left( \lambda_i \right)^2 \]  

For the two-wavelength case where \( OD_0(\lambda_0) = 0, OD_0(\lambda_1) = OD_{CO_2} S(\lambda_0) S_{offline} \) and \( S(\lambda_1) = S_{online} \), the line shape scale factor and the measurement error, Eqs. (20) and (24) reduce to the familiar formula for conventional DIAL IPDA lidar,

\[ \tilde{a}_{CO_2} = -\frac{1}{2OD_{CO_2}} \ln \left[ \frac{S_{online}}{S_{offline}} \right] \]  

and

\[ \text{var} \{ \tilde{a}_{CO_2} \} = \left\{ \frac{1}{2OD_{CO_2}} \right\}^2 \left\{ \frac{1}{\text{SNR} \left( \lambda_0 \right)^2} + \frac{1}{\text{SNR} \left( \lambda_1 \right)^2} \right\} \]  

with the SNR given by the same formula as that of the surface elevation lidar, Eq. (3b), but substituting the average number of detected signal photons by

\[ \langle n_{SIG} \left( \lambda_i \right) \rangle = \langle n_{SIG_{offline}} \rangle \exp \left[ -2 \left\{ \alpha_{CO_2} \right\} \cdot OD_0(\lambda_i) \right] = \langle n_{SIG_{offline}} \rangle \exp \left[ -2OD_0(\lambda_i) \right] \]  

The relative error of the estimated scale factor can be approximated as

\[ \epsilon_{CO_2} = \sqrt{\text{var} \{ \tilde{a}_{CO_2} \}} = \sqrt{\text{var} \{ \tilde{a}_{CO_2} \}} \]  

The total column CO\(_2\) number density is proportional to the scale factor of the precalculated optical depth function based on the atmosphere model and meteorological data, and the error in the estimated CO\(_2\) mixing ratio can be approximated as the product of the nominal CO\(_2\) mixing ratio and the relative error of the scale factor. For example, if the nominal atmospheric CO\(_2\) mixing ratio is 400 ppm and the relative measurement error of the optical depth scale factor is 0.001, the estimation error in the atmosphere CO\(_2\) mixing ratio is 0.4 ppm. Note the above derivations cover only the random error due to the receiver SNR. In practice, there are also biases in the results due to other factors, such as uncertainties in the meteorological data and drift in the instrument parameters, which can become the dominant error source and have to be calibrated out.

### 1.15.4.3 History of Laser Spectral Absorption Lidars

Laser spectral absorption lidars have long been proposed (Menzies and Chahine, 1974; Menzies, 1972; Menzies and Tratt, 2003) because of the potential improvement in the measurement precision and accuracy enabled by lasers and the ability for continuous observation day and night. However there had been a lack of laser transmitters, which not only produce sufficiently high pulse energy to ensure proper receiver SNR but also had high spectral purity and stability for this type of measurements. Recent developments of high power and high spectral purity lasers, especially fiber lasers, have made it possible to measure certain atmosphere gases from orbit. NASA has been developing a mission concept called Active Sensing of CO\(_2\) Emission over Days, Nights, and Seasons (ASCENDS) (NASA, 2008) as a second tier lidar mission recommended by the Earth Science Decadal Survey (United States National Research Council, 2007). There have been several airborne IPDA CO\(_2\) lidar developed in the United States as candidate instrument for the ASCENDS mission. These are (a) a coherent IPDA CO\(_2\) lidar with a cw laser at 2 \(\mu\)m wavelength (Spiers et al., 2011), (b) a lock-in type direct detection IPDA CO\(_2\) lidar with sinusoidal intensity modulated lasers at 1.57 \(\mu\)m wavelength (Dobler, 2013), (c) a direct detection IPDA CO\(_2\) lidar with pulse lasers at 1.57 \(\mu\)m wavelength (Abshire et al., 2014), and (d) a direct detection IPDA CO\(_2\) with pulse lasers at 2.05 \(\mu\)m laser wavelength (Refaat et al., 2015; Fefaat et al., 2016). There are advantages and disadvantages for each type of laser modulation and detection techniques, and a detailed comparison can be found in Sun and Abshire (2012).

ESA has conducted mission studies for a similar CO\(_2\) lidar mission called Advanced Space Carbon and Climate Observation of Planet (A-SCOPE) (ESA A-SCOPE, 2008) along with detailed analysis of laser wavelength selection and receiver performance (Caron and Durand, 2009; Caron et al., 2009; Ehret et al., 2008). ESA also conducted airborne CO\(_2\) IPDA lidar measurements at 2-\(\mu\)m (Gibert et al., 2008) and 1.57 \(\mu\)m (Amediek et al., 2009).

In addition to CO\(_2\) IPDA lidar, there is a strong desire to measure the global methane distribution from space (Frankenberg et al., 2005). NASA has been conducting airborne methane lidar measurement at 1.65 \(\mu\)m wavelength using a relatively low pulse energy but high pulse rate optical parametric oscillator (OPO) and optical parametric amplifier (OPA) laser (Riris et al., 2012). ESA has also conducted airborne IPDA methane lidar experiment using OPO laser at 1.65 \(\mu\)m (Amediek, 2016).

### 1.15.4.4 Future Laser Spectral Absorption Lidar and the Trend of the Technology Developments

NASA has been actively planning the ASCENDS mission with a CO\(_2\) IPDA lidar. The NASA Earth Science Technology Office (ESTO) has been funding several efforts to develop candidate CO\(_2\) lidar and conducting airborne campaigns with these instruments operating simultaneously on the same airplane since 2014. The German Space Agency (DLR) and the French Space Agency (CNES) are now developing the Methane Remote-Sensing Lidar Mission (MERLIN) mission to measure methane using IPDA lidar at 1.65 nm with an expected relative measurement error of about 1\% (Stephan et al., 2011; Kiemle et al., 2011; CNES, 2016; EOPortal-MERLIN, n.d.). The trend of the technology development is to improve the technology readiness level for space application, measurement bias control and reduction, and reduce instrument cost.
1.15.5 Conclusions

Space lidars have been unique and important tools in remote sensing. The technologies have been continuously advancing over the past 30 years. The laser efficiency and the detector sensitivities have been improved to allow multiple beam measurements from orbit within the same power and mass constraints as the early day single-beam laser rangers. The atmospheric greenhouse IPDA lidars have evolved from two-wavelength DIAL measurement to multiple wavelength sampling IPDA lidar. Lidars started to be used to measure the spectral properties of atmosphere and surface that passive spectrometers used to do, but with a unique advantage of uniform lighting and continuous day and night measurements. The laser wavelengths for lidar sensors are also expanding, from UV to mid-infrared. Airborne lidars are now used to map the terrain at multiple laser wavelengths simultaneously to reveal new features and natural process of the climate change (Carlos et al., 2016). There are more and more lidars operated at short-wave infrared (SWIR) to mid-wave infrared (MWIR) wavelength region because there are more distinct absorption lines of interested species in this wavelength band. The solar background light is much less. The laser eye safety threshold at SWIR and MWIR is much higher. There are also more lasers available in SWIR, thanks to the optical fiber communication and fiber laser industries. The SWIR and MWIR detectors have become available with high quantum efficiency and single-photon sensitivity. Lidars have been proposed to detect and quantify certain elements on the lunar surface, such as water ice, using lasers at from 1 to 3-μm absorption band (Lucey et al., 2014) (Cohen, 2016), and the same technique can be applied to Earth science remote sensing. There will be more and more lidar sensors in space in coming years.

See also: 2.03. Geometric Processing: Active Sensor Modeling and Calibration (LiDAR). 3.08. Vegetation Structure (LiDAR).

References


