Laser Altimetry Measurements from Aircraft and Spacecraft

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Invited Paper

Laser ranging instruments placed on aircraft and spacecraft platforms are capable of high resolution altimetry measurements of the topography of earth, lunar, and planetary surfaces. The laser brings to altimetry a very high brightness source that can produce megawatts or greater peak power in a pulse of only nanoseconds duration. Pulse averaging is typically not required due to the high signal-to-noise ratio possible with individual laser pulse reflections. The basis of laser altimetry is the timing of the short laser pulse for round-trip propagation between the aircraft or spacecraft and the surface to be measured. With gain-switched pulses from solid-state lasers and nsec-resolution timing electronics, meter or even sub-meter vertical range resolution is possible from aircraft altitudes of several kilometers to orbital altitudes of several hundred kilometers. The high degree of collimation of laser pulses results in laser footprints at the surface as small as tens-of-meters in size, even from orbital altitudes of several hundred kilometers. Laser altimetry can provide measurements of the structure and albedo of the target surface.

The techniques involved in the design and application of laser altimeter instruments are reviewed including a description of the instrument sub-systems required for the range and waveform measurements. Laser pulse transmitters based on the relatively new technology of diode-pumped solid-state lasers are considered. Various factors affecting laser altimeter instrument performance are discussed. These include the receiver signal-to-noise ratio, atmospheric propagation, and altimeter platform effects. Some examples of laser altimeter data are presented to illustrate the variety of possible instrument applications.

I. INTRODUCTION

The measurement of the topography of earth, lunar, and planetary surfaces can be performed at high resolution by the use of the technique of laser altimetry. The basis of the measurement is the timing of short pulses for round-trip propagation at the speed-of-light between the aircraft or spacecraft and the surface to be measured. Vertical (height) resolution of the altimetry measurement is determined primarily by laser pulsewidth and the timing precision of the altimeter electronics. With conventional gain-switched pulses from solid-state lasers and nanosecond-resolution timing electronics, meter or even sub-meter vertical range resolution is possible from aircraft altitudes of several kilometers to orbital altitudes of several hundred kilometers. Horizontal resolution is a function of laser beam footprint size at the surface and the spacing between successive laser pulses. Laser divergence angle and altimeter platform height above the surface determine the laser footprint size at the surface; while repetition-rate and altimeter platform velocity determine the spacing between successive laser pulses.

A very essential ingredient in measurement of surface topography by laser altimetry is an independent knowledge of altimetry platform pointing angle and motion. Variations in laser pointing angle can map directly into range biases and platform vertical motion can be confused with topography variability. In airborne laser altimetry, the dominant effect is aircraft vertical motion resulting from turbulence and altitude changes. In space-based laser altimetry, pointing angle effects are usually dominant due to the several hundred kilometer lever arm of the spacecraft orbit that maps angle into range bias.

Laser altimetry provides measurements of the structure and albedo of the target surface in addition to the straightforward range measurement. Surface structure (i.e., the height distribution or slope within the laser footprint) is determined by high-speed digitization of the backscattered laser pulse shape. The transmitted laser pulsewidth is typically optimized to be very short (1-10 ns or 0.3-3 m in length) for high-precision ranging. After interaction of the laser footprint with a rough or sloping surface, the backscattered pulse may contain several nanoseconds or more of pulse spreading or distortion. The application of gigahertz bandwidth digitization to this receiver pulse waveform provides pulse shape data. The backscattered pulse width (or rms pulse spreading) that is derived from these data is usually a sufficient measure of surface structure. The total area under the received pulse is proportional to the pulse energy and is a measure of surface albedo at the monochromatic laser wavelength. Effective use of this albedo data requires at least a relative calibration of laser backscatter from different surfaces and a normalization by laser transmitter energy.

The most significant distinction of laser altimeters over existing radar altimeters is the orders-of-magnitude smaller footprint that results from the narrow beam of optical radia-

Manuscript received August 15, 1988; revised October 10, 1988.

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IEEE Log Number 8825484.

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tion. Laser footprints at the surface can be as small as tens-of-meters in size, even from orbital altitudes of several hundred kilometers. These small footprints are a simple consequence of the sub-milliradian diffraction of optical fields from antenna apertures. By contrast the typical radar altimeter beamwidth is degrees in extent and the radar footprint on the surface is an annulus that expands outward from the nadir position. This contrast is illustrated in Fig. 1 for a 1-μm optical wavelength and 2-cm radar wavelength. Note that the radar has a pulse-limited footprint that results from wavefront curvature and the length of the pulse. In laser altimetry, where milliradian beamwidths are typical, the pulse-limited and beam-limited footprints are essentially identical. The radar pulse always includes nadir in its beam-limited footprint, but has the disadvantage that nadir is not necessarily the leading edge of the backscatter pulse if surface slopes are present. In addition, laser altimeter measurements complement the wide survey feature of imaging radar data by providing a high-resolution nadir ground track and by providing a series of calibrated grid points. They also can directly measure the surface micro-roughness which is the very quantity that causes the microwave backscatter intensity in the imaging radar data.

The laser also brings to altimetry a very high brightness source that can produce megawatts or greater peak power in a pulse of only nanoseconds duration. When this source is transmitted from a relatively small aperture (~ 2 cm) and received through larger optics (~ 1 m), the coherent fading that requires radar altimetry to average over many pulses in order to produce high quality range data is no longer a major factor. The result is a very high-quality measurement for individual laser pulses. No pulse averaging is required or in fact desired. Each pulse produces a unique measurement that defines the vertical and horizontal resolution of the laser altimeter.

In contrast to other laser remote sensing applications, the field of laser altimetry had its beginnings in space-based observations. A laser altimeter instrument was included in the complement of instruments in the APOLLO Command and Service Module in lunar orbit in the early 1970s. Successful operation of this first space-based laser remote sensing instrument was achieved on the three missions attempted; APOLLO 15, 16, and 17. Laser ranging data in the form of altimeter profiles of the lunar surface were acquired at a very successful rate of 99 percent for the 4000 laser pulses attempted in the APOLLO 17 mission. The data and its applications were examined by Kaula et al. [1]. This laser altimeter instrument was based on the solid-state, flash-lamp-pumped, Q-switched ruby laser that is the forerunner of present-day neodymium laser technology.

In the intervening two decades since the APOLLO Lunar Laser Altimeter there has been significant progress in the application of laser altimetry to land processes and atmospheric science measurements from airborne platforms. Laser altimetry data have resulted in profiles and maps of surface topography, coastal water depth, forest canopies, sea ice distribution, volcanic landforms, impact craters, and ocean wave heights. There also has been significant progress in solid-state laser technology. It now appears possible to construct airborne and space-based laser altimeters with a fraction of the size, weight, and power of APOLLO days, and yet performance and lifetime that exceed the original device by up to several orders-of-magnitude [2]. Most of this increase in capability is directly the result of recent breakthroughs in diode-pumped solid-state laser technology [3]. In this technology, arrays of thousands of micron-size semiconductor lasers with output power at near-infrared wavelengths are used to excite conventional solid-state crystal laser materials. Pulsed laser transmitters based on this technology are just now becoming available.

The techniques involved in the design and application of laser altimeter instruments will be reviewed in the following section. This will include a description of the instrument sub-systems required for the range measurement and the waveform measurements. Then the various factors affecting laser altimeter performance will be considered. These include the receiver signal-to-noise ratio (SNR), atmospheric propagation, and altimeter platform effects. Various examples of laser altimeter data will be presented to illustrate the variety of possible instrument applications. The paper will conclude with a review of possible space-based laser altimeter applications.

![Fig. 1. Comparison of laser and radar altimetry.](image-url)
II. Laser Altimetry Techniques and Measurements

Fig. 2 illustrates the measurement possibilities in laser altimetry by providing the time varying amplitude of an altimeter detector that observes both the transmitted and backscattered laser pulse. The series of regularly-spaced marks along the base of the received pulse indicates the location of waveform digitization samples. Note that the received pulse is generally spread and distorted by interaction with the target surface. Data quality is directly affected by the pulse spreading encountered in backscatter from rough or sloping surface targets and clouds. Pulse spreading, by re-distributing the available pulse energy into a larger time interval, acts to reduce the peak-power SNR, thus increasing the probability of error for the range measurement. Pulse spreading also adds timing uncertainty by slowing the rise time of the return signal and thus increasing the dependence of the threshold crossing time on pulse amplitude. The time interval data, waveform digitizer data, and pulse energy data form the basic laser altimeter dataset for each laser pulse. These data points are accumulated in a buffer in digital form, formatted into data blocks or files, and then enter the altimeter platform data stream for recording or telemetry.

High-resolution laser altimetry requires some pointing control of the laser beam to maintain alignment near nadir and requires extremely accurate knowledge of altimeter attitude in order to compute angular offset from nadir and preserve range measurement accuracy. The interaction of a finite laser beamwidth \( \Delta \phi \), an angular offset \( \phi \) from nadir, and a surface slope \( S \) can produce significant spread \( \Delta T \) beyond the nominal laser pulse width \( \Delta T \). This concept is illustrated in Fig. 3 with a surface slope of the same polarity as the pointing angle offset from nadir. Pulse spread can be determined from the derivative of laser propagation time to the surface with the result that

\[
\Delta T = \left( \frac{2c}{T_0} \right) \tan (\phi + S) Z \Delta \phi
\]

where \( c \) is the speed of light, \( Z \) is the slant range to the surface, and we have made the assumption that surface reflectivity is uniform throughout the laser footprint on the surface. This is essentially the result quoted by Gardner [4] and Im and Gardner [5]. The parameter \( \Delta \phi \) can be interpreted as either the laser divergence angle or the uncertainty in altimeter pointing angle. When \( \Delta \phi \) is laser divergence, (1) can be used to compute the time spread across the laser footprint. When rms pointing uncertainty is substituted for \( \Delta \phi \) in (1) the result is a computation of rms pulsewidth uncertainty or range error \( \Delta Z = c \Delta T / 2 \). Note that surface slope can either add a pulse spread or reduce it depending on slope polarity with respect to the angular offset from nadir. For example, assume for a laser altimeter in lunar-orbit the values of \( Z = 100 \text{ km} \), \( \Delta \phi = 10^{-3} \text{ rad} \), and \( \phi = 0.1^\circ \). For a surface slope of \( S = 1^\circ \), then \( \Delta T = 12.8 \text{ ns} \). An original laser pulse of 5 ns width is spread by a factor of about 2.5. Timing accuracy is obviously degraded for this wide pulse and there is also a question as to interpretation of the range measurement at the sub-meter level.

Fig. 4 is a plot of \( \Delta Z \) as a function of surface slope for a 100 km orbital altitude and \( \phi = 0.1^\circ \) for several values of \( \Delta \phi \).

Sloping target surfaces aggravate the effect of pointing error on altimetry accuracy since they act in the same way as a nadir offset angle. Attitude must be measured to the 20 arcsec level (100 \( \mu \text{rad} \)) for each laser pulse for any appreciable pointing offset from nadir if sub-meter ranging precision is to be maintained. Even with accurate pointing and pointing angle knowledge, the presence of surface slopes will unavoidably degrade laser altimetry range accuracy. Range error, \( \Delta Z \), can be substantial at an 800 km orbital altitude for even modest surface slopes if \( \Delta \phi \) is not at the few arcsec level. The scale factor relating altimetry range error to laser pointing uncertainty for a flat target surface at one degree off-nadir is 7 cm/arcsec at this altitude.

The concept of a laser altimeter instrument appears in Fig. 5. This view illustrates the laser transmitter module, receiver telescope, detector package, ranging and waveform electronics, and pointing attitude measurement components that form the major instrument subsystems. These
subsystems are packaged into a common structure that provides a rigid platform for the laser transmitter and receiver optical components. The size of this structure is primarily dependent on telescope aperture, which in turn is sized for the particular propagation pathlength to the target surface.

The pulsed transmitter is based on the high-power, neodymium yttrium aluminum garnet (Nd:YAG) solid-state laser. The conventional flashlamp-pumped Nd:YAG has an electrical-to-optical efficiency of 1–2 percent and a typical lifetime of at least $10^7$ pulses. At this level-of-performance it is the leading laser for ground-based and airborne laser ranging applications, either at the fundamental wavelength of 1.06 μm or the frequency-doubled wavelength of 532 nm. These wavelengths match respectively with silicon avalanche photodiode detectors and photomultiplier tubes for efficient laser ranging system operation.

Recent improvements in the peak power, brightness, and availability of semiconductor laser diodes and arrays are now making practical diode-pumped Nd:YAG lasers a reality [6]. Researchers currently report one order-of-magnitude improvement in pumping efficiency and two-orders-of-magnitude improvement in laser lifetime (i.e., 10 percent efficiency and $10^8$ pulses) when the Nd:YAG laser pumping is provided by aluminum gallium arsenide (AlGaAs) semiconductor laser diodes whose output near 808 nm matches strong Nd:YAG absorption lines. This synergism of solid-state lasers appears to offer all the features of efficiency, lifetime, solid-state reliability, and compactness that are very useful in airborne instrumentation systems and absolutely essential on spacecraft. It should be noted that a variety of solid-state materials in addition to Nd:YAG are under investigation for diode-pumped laser construction in an effort to optimize the efficiency and the output wavelength of this device.

Fig. 6 illustrates the construction of a diode-pumped Nd:YAG laser oscillator. The optical coupling of laser diode
emission to the laser host material involves side-pumping by multiple two-dimensional laser diode arrays in an effort to force as much pump energy as possible into the laser host material as described by Hanson and Haddock [7]. In Nd:YAG the lines from 806 nm to 890 nm yield absorption coefficients of 3–6 mm\(^{-1}\), with conventional 1 percent Nd doping to 10 mm\(^{-1}\) for 1.6 percent doping. As a result the laser crystal need only be a few millimeters thick. Temperature stabilization with thermo-electro coolers removes waste heat from the laser diode arrays and brings their output wavelength to the 808 nm optimum pumping wavelength for Nd:YAG at a rate of 0.3 nm/C. Cooling shortens the laser diode array output wavelength. The laser crystal in the illustration is a small slab (platelet) only 1 cm long. A hemispherical cavity is formed between the 100 percent mirror and a 70–90 percent reflectivity of the concave output coupler. Pulse width is determined by laser cavity length (L in cm) and reflectivity (R) of the output coupler according to the formula [11]

\[
\Delta T = \frac{nLc}{-\ln(R) + a} \left[1 - \frac{1}{r} \left[1 + \ln(r) + a\right]\right]^{-1}
\]

where

- \( n \) = effective refractive-index of the laser cavity,
- \( c = 3 \times 10^8 \) cm/s,
- \( a \) = laser material scattering and absorption losses,
- \( r \) = ratio of single pass cavity gain to cavity loss = \( \exp(gL)\left[\ln(R) + a\right] \),
- \( g = \frac{sE(h\nu\gamma)}{A} \),
- \( h \) = Planck’s constant,
- \( v \) = laser optical frequency,
- \( s \) = stimulated emission cross section (cm\(^2\)), and
- \( A \) = gain medium cross-sectional area.

The Q-switch switching time is effectively included in the loss factor a. Switching times on the order of a few nanoseconds can be routinely achieved, very small pathlengths can be employed for the laser cavity, and the output coupler reflectivity can be chosen to simultaneously minimize \( \Delta T \) and maximize output pulse energy. The laser oscillator illustrated in Fig. 6 is designed to produce a pulse of 5 ns width and a pulse energy of 10 mJ using an LiNbO\(_3\) Q-switch.

In laser diode-pumping the electrical current input to the diode must first reach the lasing threshold and then the laser diode optical input must reach the lasing threshold of the host laser material. Above threshold the slope efficiency is the relevant figure-of-merit. The overall electrical-to-optical pumping efficiency can be computed by considering the following efficiency factors: 1) diode efficiency, 2) optical coupling efficiency, 3) absorption efficiency, 4) photon-energy ratio (0.76 for Nd:YAG), and 5) pulse-pumping efficiency (0.67 for 200 \( \mu \)s in Nd:YAG). The high-power laser arrays recently have been reported by at least two manufacturers to have an electrical-to-optical efficiency of about 40 percent [12]. If both coupling and absorption approach 100 percent, the remaining factors yield an optical slope efficiency as high as 50 percent in Nd:YAG. Thus for Nd:YAG the total laser slope efficiency (electrical-to-optical) can reach 20 percent. The laser oscillator illustrated in Fig. 6 is pumped well below saturation in the laser platelet, so that threshold effects are still important. The result should be an optical-to-optical efficiency of about 10 percent and an electrical-to-optical efficiency of about 5 percent.

The laser diode-pumped Nd:YAG oscillator can be followed by a diode-pumped laser amplifier. In this concept, multiple laser diode array pumps, each capable of 25-mJ pump energy, are used to store energy in a Nd:YAG slab. A zig-zag slab geometry is typically used to maximize the optical gain length in the slab and pumping can be con-

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centrated at the reflection points in order to maximize pump-to-beam coupling. The oscillator amplifier combination should be capable of >30-mJ output pulse energy with only minor stretching of the original 5 ns pulsewidth. The major challenge in amplifier design is efficient extraction of the stored energy. Extraction is proportional to input pulse energy density (fluence) and to optical gain length. Multi-pass diode-pumped Nd:YAG amplifier schemes, as described by Chan [13], can improve on extraction efficiency for the typical low fluence input from a diode-pumped oscillator.

The optical system of the laser altimeter, as illustrated in Fig. 5, is composed of the diode-pumped laser, transmitter optics, and a relatively large diameter receiver telescope. The transmitter optical system uses only one turning mirror to direct the output laser pulses parallel to the receiver optical axis. All transmitter-to-receiver boresight in the altimeter instrument is accomplished by the two-axis gimbal mount that holds this turning mirror. A variable beam expander telescope controls laser divergence angle in order to achieve the desired laser footprint size in the altimetry application. The beam expander telescope also reduces boresight errors in the turning mirror by the beam expansion ratio. Output for the beam expander can provide a transmitter beam divergence as low as 0.1 mrad with a beam diameter of about 5 cm after expansion of the typical low-order transverse-mode pattern of the Nd:YAG laser. This requires approximately 10x expansion (collimation). Boresight between transmitter and receiver must be maintained to a fraction of the divergence in order to ensure that the entire laser footprint is seen by the detector.

If the required laser beam divergence is on the order of 0.1 mrad, a further refinement of the transmitter optics may be needed. Beam angle sensors may be necessary to sample laser pointing attitude for each pulse. A beam angle sensor can be implemented with a quadrant photodiode and appropriate focusing optics to achieve an angular sensitivity of arc seconds. A silicon p-i-n diode could also be mounted at the location of the beam angle sensors and turning mirrors to sample the time dependent signal characteristics of the output laser pulse for the altimetry data stream. Alternately, a fiber optic bundle can be used to relay a small fraction of the transmitted laser pulse to the receiver optical detector. This method is particularly useful in minimizing the measurement bias in the altimeter, since both transmitter and receiver pulse waveforms follow the same electronic path.

The primary mirror of the receiver telescope is sized to achieve a desired signal collection area for laser radiation backscattered from the target surface. It is this mirror size that largely determines the size and weight of the receiver telescope. The use of modern lightweight mirror technology can result in significant reductions in the overall size and weight of the telescope assembly. In addition, the process of diamond-turning can be employed to achieve the final optical figure of the primary mirror. Diamond-turning is a practical choice since the optical quality of the primary mirror can be less than diffraction-limited. In contrast to conventional high-resolution imaging in astronomy, the role of the laser altimeter telescope is only the collection of photons from the extended object of the laser beam footprint on the target surface. For example, an acceptable image blur circle (of a point source) for a 0.5-m-diameter altimeter mirror can be a 100-μm spot at 1 μm wavelength versus a diffraction-limited 2.5-μm spot. The diamond-turning process is particularly well suited to aluminum substrates which are easily machined for light-weighting. After fabrication of the aluminum substrate, the final optical surface of the primary mirror is obtained by electro-less nickel coating (~1 mm thick), diamond-turning of the nickel surface, and then evaporative coating with gold [14].

Although detection can take place at the prime focus of the primary mirror, it is often more desirable to use a secondary mirror to fold the receiver optics and locate the detection plane behind the primary mirror, as illustrated in Fig. 5. This method has the added advantage of reducing the length of the telescope tube. If both primary and secondary mirrors are constructed with on-axis parabolas, a beam-condenser design results. For example, a 0.5-m-diameter concave, parabolic primary mirror together with a 0.025-m-diameter convex, parabolic secondary mirror results in a 15:1 beam condenser. An optical bandpass filter 2 nm wide, centered on the transmitted laser wavelength is placed in the collimated ray bundle produced by the beam condenser. This filter is designed to reject solar backscatter for daytime altimetry operations with a bandpass filter transmission of 0.70. This combination is followed by refractive optics to concentrate received optical energy on the detector. Receiver optical train efficiency should be about 0.5.

The silicon avalanche photodiode (Si APD) reported by Webb and McIntyre [15] with sufficient bandwidth (~50-100 MHz) for short-pulse detection, has an active area of 0.8 mm diameter. It makes use of a double-diffused "reach-through" structure for enhanced Si APD breakdown at 1.06 μm. The Si APD is biased at a high voltage (~300 V) and is connected to a GaAs FET low-noise pre-amplifier to form the altimeter detector for operation at 1 μm. All these electronics [16] operate from +12 V dc input power. The combination of Si APD and the pre-amplifier yields a detection sensitivity near 3 x 10^-16 W. This is about one order-of-magnitude greater than the photon-noise limit at 1 μm wavelength calculated for a time duration equal to the reciprocal of the bandwidth. If frequency doubling is used, the laser output wavelength of 532 nm is detected most efficiently with a photon-noise-limited photomultiplier tube (PMT). Quantum efficiencies are respectively 40 percent at 1 μm, and 25 percent at 532 nm for the Si APD and PMT, respectively.

The field-of-view for the receiver system is typically set to about 1.5-2 times the angular subtense of the laser beam footprint. Both receiver optical bandpass and field-of-view are detection parameters that should be reduced to the smallest values that are practical in consideration of the competing processes of maintaining a high level of detection optics throughput, operating under conditions of solar backscatter, and ensuring that radiation from the entire laser footprint is focused onto the detector.

The altimeter electronics are used to process the pulse waveforms from the detector(s) to arrive at measurements of range-to-the-surface, surface reflectance, and surface vertical structure within the laser footprint. A detailed block diagram of these electronics appears in Fig. 7. The analog pulse waveforms are split to start and stop the time-interval unit, measure pulse energy, pulse power, and pulse width, and provide input to the waveform digitizer. Note that Fig. 7 illustrates the preferred method of using a single detector.
Fig. 7. Laser altimeter receiver and processing electronics.

for transmitted and received pulses, so that all pulse measurements are made with the same electronics. The time-interval unit (TIU) is a time-to-digital-converter of at least 1 ns time-interval resolution (corresponding to 15 cm range precision). It is based on a high-frequency oscillator, counter, and interpolation circuitry. Pulses input to the TIU are first processed by threshold-detection discriminators whose outputs are fast risetime pulses of standard amplitude and width. The front-end circuitry of the discriminator and TIU are based on ECL logic and GaAs logic in order to achieve the nanosecond-level of resolution.

The waveform digitizer performs high-speed waveform sampling that operates continuously with a re-circulating memory. The output of the receive pulse discriminator is used as a stop pulse for the digitizer, thus providing self-gating capability. The received pulse amplitude is digitized into 50-100 waveform slices. Each slice is on the order of 1 ns in duration for sub-meter-level resolution of pulse spreading. The number of channels is selected to permit digitization over a time interval that includes the entire receive pulse while still retaining the self-gating feature. Any pulse spreading induced by the target’s surface slope or roughness acts to re-distribute laser pulse energy into a broadened waveform. It may be desirable to provide multiple TIU electronics in order to handle the wide dynamic range of pulse spreading that is likely to occur with actual target surfaces and large laser footprints. For example, the 1 nanosecond-resolution amplifier, discriminator, and TIU described above could be supplemented by a 10 ns resolution channel that would improve the signal-to-noise of the range measurement for situations in which target-induced spreading is at the several meter level. Both the TIU and waveform digitizer electronics are connected through a digital command and data interface to the altimeter computer.

One of the power splitter outputs for the receive channel can be directed into a separate threshold-discriminator and counter circuit for the purpose of assessing the average background-noise level. Detector output noise pulses due to solar background or internal noise are counted over a relatively large fraction of a second and the result used to adjust the programmable attenuator that acts on the receive pulse. The resultant servo-loop acts to maintain a near optimum electronic gain in the receiver pulse circuitry. Thus under high background conditions gain is reduced to prevent false triggering while under low background conditions gain is increased to provide a maximum probability-of-detection. This adaptive threshold is potentially quite important in altimetry observations of the earth’s surface where rapid, large albedo variations are common due to laser backscatter from clouds and bodies of water. The electronic filter preceding the ranging discriminator can have a programmable bandpass in order to improve the SNR for backscatter pulses that are spread (thus lower bandwidth) by interaction with the target surface. Alternately, a second or third time-interval channel acting in parallel to the first channel can be implemented with a different electrical filter bandwidth.

Control of laser operation, acquisition of altimetry data, maintenance of an updated pointing attitude and position estimate, sequencing of altimeter instrument operations, and measurement of payload temperatures, voltages, and other housekeeping data are all duties of the altimeter payload computer. This device is typically based on a microprocessor that optimizes processing and data transfer speeds with the requirement for reliable, low-power operation. On-board data buffering is provided by solid-state memory electronics. A master software program steps sequentially through various loops to fire the laser, read the TIU, digitizer, pulse measurement electronics, position and pointing attitude electronics and acquire housekeeping data. During these operations the program must verify data quality as it is being acquired. A major function of the computer program is also the formatting of altimetry and housekeeping data and the control of data transfer to the telemetry system or a master computer.

The pointing-attitude measurement sub-system, as illustrated in Fig. 5, depends on the altimetry application for its composition. In a full-performance space-based laser altimeter, an inertial reference unit and two star trackers would be used to make available an absolute attitude estimate for precise knowledge of the angular offset from nadir.
additional part of this sub-system would be a Kalman filter software package in the instrument computer. This software processes star tracker data for frequent up-dating of the inertial reference unit. The reference platform is the surface of the optical bench. Button et al. [17] reported the results of a computer-simulation of the accuracy with which standard star trackers and inertial reference unit can estimate instrument attitude. The results were about 10 arcsec rms and were limited primarily by star tracker data quality. Recent improvements in star tracker data quality have resulted from the upgrading of device digital electronics so than 5 arcsec rms attitude determination is possible. The beam angle sensors measure the angular orientation of each laser output pulse with respect to the inertial reference unit. This type of system is appropriate for a spacecraft platform, which due to its high altitude (~800 km in earth-orbit) above the target surface, has the most stringent requirement (~25 μrad) on pointing attitude knowledge. Laser altimeters in lower orbits can use horizon sensors and gyro to measure pointing angles. An aircraft platform at several kilometer altitude, requires only mrad knowledge of pointing attitude. This can readily be achieved by conventional roll and pitch gyro sensors.

In addition to instrument attitude it is very important to know altimeter platform position. Knowledge of horizontal position to dimensions on the order of the laser footprint size is important for locating the altimeter ground track and relating data between successive tracks over specific target areas. Knowledge of vertical motion of the altimeter platform must be at the sub-meter level, since this has an obvious effect on the measured altimeter range. Data from a sensitive vertical accelerometer can be twice integrated to remove altimeter platform vertical motion from a short segment of laser data. The monitoring of position in three dimensions can be accomplished by including a Global Positioning System (GPS) receiver on the platform and continuously recording position data. When the GPS satellite network is fully operational, the precision of aircraft and spacecraft position determination is on the order of 1 meter. The GPS technique of altimeter platform position determination has been verified by Krabill and Martin [18] from an aircraft platform.

The use of a laser altimeter for data collection over specific target sites, imposes constraints on design of the instrument, its operational use, and the need for auxiliary data sets. First, the desire for contiguous nadir profiles over relatively small targets requires high-quality data for each laser pulse. There is no opportunity for multiple pulse averaging. Second, there is usually a need for a small footprint on the target surface. Typical values are a few tens-of-meters to a hundred meters. For example, analysis by Zwally et al. [19] has shown that the optimum laser altimeter footprint size on an ice-sheet surface is only 70 m. This footprint size is determined by the need to average over small-scale ice-sheet roughness while fully resolving the major components of ice-sheet surface height variability. The operation of the laser altimeter on an 800 km altitude polar platform results in a 0.09 milliradian divergence angle in order to produce the desired footprint. When these two requirements are combined, the result is a requirement for high repetition-rate acquisition of altimetry data.

High repetition-rate operation is quite demanding in terms of laser lifetime, power consumption, thermal dissipation, and telemetry data rate. It is not too severe a problem on aircraft or a large polar platform spacecraft, since the laser altimeter occupies a small percentage of the total platform capacities. But it may be very critical on a small one-instrument spacecraft in earth orbit, or a small observer-class spacecraft in lunar or Martian orbit. One way the demands of high repetition-rate operation can be more easily accommodated is through the use of a burst mode of laser operation. For example, nominal operation of a lunar laser altimeter could be set at a rate of 10–20 Hz with 100–300 m footprints on the lunar surface. This would provide wide area profiling of the lunar surface. Instrument average power, equilibrium temperature, and nominal data rate would be determined by this low-to-moderate pulse-rate operation and the interface limitations set by the host spacecraft. Then for selected study sites or short periods of time, the laser repetition-rate could be increased to 50 Hz and the footprint narrowed (by reduction of transmitted laser divergence angle) for a burst-mode of operation that would provide higher-resolution altimetry data.

III. LASER ALTIMETRY PERFORMANCE

The laser altimeter concept we have described is based on a high signal-to-noise environment in which each laser pulse can be used for a unique range measurement. For terrain profiles it is most important to preserve the independent data of each successive pulse in order to maximize horizontal resolution while simultaneously minimizing laser pulse rates. Altimetry performance analysis requires verification that an adequate detection SNR is present and quantification of the relationship between SNR and the altimetry data products.

Laser altimeter signal strength depends on laser pulse power backscattered from the target surface and collected by the receiver telescope. Competing processes are optical shot noise, background noise, detector noise, and pre-amplifier noise. Calculations of these quantities can be used to establish a detection SNR for comparison with measurements of SNR in altimeter field tests. Furthermore, the time-interval (i.e., range) measurement is based on timing of pulses that exceed a threshold. Only those pulses which exceed the threshold enter into the data stream. This threshold circuit helps suppress the effect of background and detector noise, thus minimizing the probability of false alarm (PFA), but also reduces the probability of detection of laser pulses. For a given altimeter electronic configuration there is a unique relationship between detection SNR and probability of detection or the related quantity probability of error (P(E)).

For nadir-viewing altimetry operation the lidar or link equation for received laser pulse power \( P_R \) can be written as

\[
P_R = \frac{E_I A_R}{\Delta T Z^2} T_o T_c^2 T_2^2 (\nu/\Omega) \tag{3}
\]

where

- \( E_I \) = transmitted laser energy (J),
- \( \Delta T \) = laser pulse width (s),
- \( A_R \) = receiver area (m²),
- \( Z \) = range to the surface (m),
- \( T_o \) = optical system transmission,
- \( T_c \) = cirrus cloud transmission.

\[\text{PROCEEDINGS OF THE IEEE, VOL. 77, NO. 3, MARCH 1989}\]
The value of \( T_o \) is dominated by the 70 percent transmission of the 20 Å bandpass optical filter in the receiver. This bandwidth is near optimum in terms of providing the maximum reduction in solar background flux, while maintaining a high throughput. The result is an overall value of \( T_o = 0.50 \) for transmitter and receiver. The value of \( n/\Omega \) varies over an order-of-magnitude dependent on the spectral reflectance and angular scattering properties of the target. At 1.06 µm on earth \( n/\Omega \) ranges from 0.05/π-0.8/π sr\(^{-1}\). For instance, terrain and ice have values from 0.2/π-0.8/π sr\(^{-1}\) [20, 21], and the ocean surface near nadir ranges from 0.05/π-0.3/π sr\(^{-1}\) [22].

The inverse square-law dependence of \( \text{PR} \) on \( Z \) is the dominant factor in determining the size and power consumption of the laser altimeter payload. The designer must compensate for large \( Z \) by increases in \( P_t \) and \( A_o \), where the term \( P_t \) is the peak power of the transmitted laser pulse. Its exact value depends on pulse shape, but is essentially equal to \( E_t/\Delta T \). Altimeters in aircraft, earth-orbit, or Martian-orbit must also contend with atmospheric-induced signal degradation, represented in (3) by the terms \( T_c \) and \( T_a \). Typical values for aerosols at 1.06 µm wavelength reported by Shettle and Fenn [23] and for cirrus clouds by Kneizys et al. [24] combine to produce a multiplicative factor of 0.25-0.5 in (3).

The laser altimeter receiver noise analysis and subsequent calculation of SNR must consider solar background irradiance, detector noise, and pre-amplifier noise as well as signal-induced quantum noise. In the case of an earth-orbiting or airborne laser altimeter the solar background irradiance reflected from the terrestrial surface and clouds can produce the optical noise power

\[
P_R = I_S A_o T_A^2 (r/\Omega) R_o T_e F_B
\]

where

- \( I_S \) = exo-atmospheric solar spectral irradiance = \( 6.6 \times 10^{-3} \) W/m\(^2\) Å at 1.06 µm wavelength,
- \( R_o \) = receiver field-of-view (sr),
- \( T_e \) = receiver optical transmission,
- \( F_B \) = filter bandpass (Å), and
- \( A_o \), \( T_A \), and \( n/\Omega \) are as given before.

The value of \( R_o \) is set at about 1 mrad in order to ensure collection of laser backscatter from the entire footprint and compensate for transmitter/receiver boresight errors. With a filter bandpass of 20 Å the worst-case \( (r/\Omega = 0.8 \text{ sr}^{-1}) \) solar background power is about \( 5 \times 10^{-5} \) W for a 0.5-m-diameter receiver telescope. The effective lower limit on daytime solar background is achieved with nadir viewing of the ocean surface, where we estimate a \( P_R \) of \( 2 \times 10^{-2} \) W for the few percent albedo of the ocean. In Martian orbit the greater distance from the sun reduces \( I_s \) to \( 2.8 \times 10^{-2} \) W/m\(^2\) Å, \( T_A^2 \) is variable but generally higher than on earth, and surface reflectance \( n/\Omega \) is within the range of variability found on earth. In lunar orbit \( I_s \) is the same as for earth, but there is, of course, no atmosphere and \( n/\Omega \) is in the range of 0.05/π-0.4/π sr\(^{-1}\).

The Si APD contributes both dark current and multiplicative excess noise to the detection process. Thermal noise at the pre-amplifier input must also be included. The overall SNR for detection of the backscattered laser pulse can be written after McIntyre [25], Webb et al. [26], Trakalo et al. [27], and Helstrom [28]

\[
SNR = \frac{P_B^2 Q \left( 2q(P_R R_o + P_R R_o + i_d) M^2 B F B R_o^2 + i_d^2 (R_0 M)^2 \right)}{4 e}
\]

where

- \( M = \) Si APD gain (≈ 120),
- \( F = \) Si APD excess noise factor (≈ 4.5),
- \( B = \) detection bandwidth (≈ 50 MHz),
- \( R_0 = \) Si APD responsivity at unity gain (≈ 0.3 A/W),
- \( q = 1.6 \times 10^{-19} \) A \( \cdot \) s,
- \( i_d = \) Si APD dark current that undergoes amplification, and
- \( i_d = \) pre-amplifier input current noise (≈ 6 \times 10^{-11} A).

The typical values indicated in (5) for \( M, F, B, R_0, \) and \( i_d \) pertain to the RCA Model C30954E SiAPD and Analog Modules LNVA pre-amplifier with GaAsFET input stage that are representative of the state of the art in silicon APD receiver technology. Equation (5) also includes the effect of signal quantum-noise by the presence of \( P_R \) in the denominator. The 50-MHz detection bandwidth is appropriate for maximizing SNR in a low-pass filter receiver for a 5 ns pulse-width [29].

The results presented in Table 1 summarize the instrument parameters and the calculations of \( P_B \) and \( P_R \) based on (3)-(5) for five laser altimeter applications: 1) a geoscience laser altimeter in an 800-km earth orbit; 2) a lunar laser

<table>
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<tr>
<th>Table 1 Summary of Airborne and Space-Based Laser Altimeter Parameters</th>
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<td><strong>Parameter</strong></td>
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<tr>
<td>Output laser energy (mJ)</td>
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<tr>
<td>Pulse repetition-rate (pps)</td>
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<tr>
<td>Distance to the surface (km)</td>
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<td>Atmospheric transmission (2-way)</td>
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<td>Laser footprint at the surface (m)</td>
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<td>Receiver telescope diameter (m)</td>
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<td>Optical signal power* (AT = 5 ns)</td>
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<td>Optical signal power* (AT = 50 ns)</td>
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<td>Optical background power*</td>
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<tr>
<td>Volume (m³)</td>
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*In units of \( 10^{-4} \) W.
Satellite altimeter in a 100-km orbit; 3) a Martian laser altimeter in a 360-km orbit; 4) a high-resolution airborne system in operation at altitudes up to 12 km; and 5) a very high-resolution airborne system for operation at about 1 km altitude. In each case the propagation pathlength $Z$ is combined with the specific mission requirements on size, weight, power, footprint size, and repetition-rate to arrive at the primary design choices of $E_r$, $\Delta T$, and $\Delta \lambda$. Table 1 includes calculations of $P_E$ and $P_F$ for $\Delta T = 5$ ns and receiver bandwidth of 50 MHz and the corresponding values for the case of 10 times pulse spreading ($\Delta T = 50$ ns) calculated for a corresponding 10 times reduction in receiver bandwidth ($B = 5$ MHz). Note that the computer values of $P_E$ that result are in the range of $10^{-8}$ to $5 \times 10^{-4}$ W. These contrast with optical background power levels $P_b$ of $10^{-8}$ to $5 \times 10^{-3}$ W.

The SNR results of (5) are plotted in Fig. 8 as a function of $P_E$. The family of three curves covers the expected range of solar background power up to $10^{-3}$ W, as well as the expected range of $P_E$ for the various applications in Table 1. It appears that SNR values in excess of 30 dB are achievable in these applications when $P_E$ exceeds $10^{-7}$ W. In fact, with the receive signal power $P_E$ exceeding $P_b$, the major noise term is signal-induced quantum noise, multiplied by the Si APD excess noise factor $F$ (detector noise). It is very important to understand that the calculations plotted in Fig. 8 are for undistorted receiver pulse waveforms (i.e., the pulsewidth, $\Delta T = 5$ ns, is preserved upon reflection of the laser pulse from the target footprint). Actual sensor footprints are likely to involve significant surface texture and have a nonzero slope. The result is degradation of the value of $P_E$ by the pulsewidth expansion ratio. Fortunately, the SNR does not suffer a proportional degradation under pulse-spreading conditions, if a corresponding reduction in receiver bandwidth is used to match the wider pulse.

Distance measurement precision is inversely proportional to SNR due to the timing uncertainty that results from signal amplitude variations combined with a fixed threshold level. The signal variation results in an rms range error $\Delta Z$ that can be estimated from the expression quoted by Salwen [30]

$$\Delta Z = c \cdot \Delta T / 2 \sqrt{SNR}$$

where $\Delta T$ is the laser pulse width. The result for a 5 ns-wide laser altimeter pulse is a $\Delta Z$ of 0.25 m for a SNR of 5 dB improving to 0.05 m for a SNR of 20 dB. Even for relatively low SNR, the error in range is small for a 5 ns pulse. We must remember, however, that a typical backscattered pulse will be spread up to one order-of-magnitude or more. The range measurement precision $\Delta Z$ is directly proportional to this spreading so that a 50-ns-wide pulse requires SNR = 18 dB to keep $\Delta Z < 1$ m. When $P_E$ drops below $10^{-9}$ W, the SNR analysis should be cast in terms of photo-electron statistics as discussed by Abshire [31], e.g., the 40 percent quantum efficiency of the Si APD results in only 11 photo-electrons for $P_E = 10^{-9}$ W at 1.06 $\mu$m for the basic 5 ns pulsewidth.

The expression for $\Delta Z$ applies only to the case where a successful range measurement is made. A low and variable SNR also produces a significant probability of error $P(E)$, and probability of false alarm $P(FA)$. These parameters are frequently used for characterizing radar performance and are potentially much more important than the degradation in ranging precision due to pulse spreading or low SNR. Under the assumption of Gaussian statistics for the detection noise processes, Fried and Schneltzer [32] have applied communication theory to the calculation of $P(E)$, the probability of missing detection of the backscatter pulse (error) in a laser range measurement

$$P(E) = \frac{1}{\sqrt{2\pi N^2}} \int_{-\infty}^{\infty} \exp \left[ -\left( t - \frac{s}{2N} \right)^2 / 2N^2 \right] dt$$

$$= \text{erf} \left( \frac{T}{\sqrt{N}} - S/N \right) + \text{erf} \left( S/N \right),$$

where $T$ is the threshold value (in signal units) set in the receive pulse discriminator, $N$ is the rms detection noise (in signal units), $TIN$ is the threshold-to-noise ratio, and $SIN$ is the square root of SNR in (5). Likewise $P(FA)$, the probability of triggering the range measurement on some form of detection noise is given by

$$P(FA) = \frac{1}{\sqrt{2\pi N^2}} \int_{-\infty}^{\infty} \exp \left[ -\left( t + \frac{s}{2N} \right)^2 / 2N^2 \right] dt$$

$$= \text{erf} \left( T/N - S/N \right) - 1/2.$$
A $P(E)$ of $10^{-3}$ or less should be acceptable in laser altimetry operations. This level of $P(E)$ can be achieved at ever lower values of $SIN$ as $T$ is reduced. But from (8), low values of threshold $T$ evidently cause higher $P(FA)$. Referring again to Fig. 8, it appears that for $T = 5 \times 10^{-7}$ W we can maintain $P(FA)$ at an acceptable level of $10^{-3}$ or lower as long as $P_{F} < 10^{-4}$ W. From (7) the simultaneous requirements for $P(E)$ of $10^{-4}$ or lower requires an $SIN$ of greater than 4 (i.e., an $SIN$ of at least 12 dB) and thus a $P_{F} > 10^{-4}$ W.

This simple analysis should be improved in at several ways in order to accurately describe the performance of laser altimeter receivers. The first improvement is in the description of receiver noise with an APD detector. As noted above there is an excess noise factor $F$ that must be included in the calculation of $SNR$ in APD detection. While the factor $F$ accounts for effects of APD noise in an rms sense, a main characteristic of this noise is rare, large amplitude bursts that are not predicted in the assumption of Gaussian statistics. Thus the results of (11) for $P(FA)$ must be considered as somewhat optimistic. The strength and frequency of occurrence of these bursts are dependent on the particular APD and on its high-voltage bias point. Each APD receiver will require testing to determine $P(FA)$ as a function of threshold setting. The second improvement concerns the signal statistics.

Pulse-to-pulse variability in the received signal strength results in considerable variation in $SNR$. The received signal fluctuates due to multiplicative factors of surface albedo, pointing-angle and target-induced pulse spreading, and atmospheric transmission variability due to aerosol and cirrus cloud scattering processes. The combination of effects can be modeled by a log-normal probability distribution for the received signal; once again a departure from Gaussian statistics. Fried and Schneiter [32] have derived a result for $P(E)$ for this more complex distribution and expressed the answer in terms of the additional link margin in decibels required to compensate for a fluctuating signal. They show that 6 dB more signal is required for a 36 percent signal modulation (i.e., when $SNR = 8.9$ dB) and 10 dB for a 52 percent signal modulation (i.e., when $SNR = 5.7$ dB). The combination of these results argues for maintenance of an $SNR > 15$ dB.

Another process with potential for modulation of detected signal strength is speckle noise. This process is a major limitation to radar altimetry that necessitates averaging over 10–100 radar pulses in order to achieve adequate $SNR$. Speckle noise, sometimes called coherent fading, is produced by interference of electromagnetic (radar or laser) radiation reflected from various portions of the altimeter footprint during the pulse duration at the target surface. Interference results from coherence in the backscattered radiation and phase differences produced by variation in the backscatter propagation distance across the footprint.

If the spatial scale of the speckle pattern in the receiver plane is smaller than the size of the receiver aperture, the contrast of the speckle interference pattern will be reduced as will the overall signal modulation due to speckle. This process is called aperture-durating at the target surface. The speckle spatial scale is proportional to $AZ$ and inversely proportional to footprint size $d$. For example at $\lambda = 1 \mu m$, a transmitter beam divergence of $\theta_t = 1$ mrad yields a spatial scale of speckle of only 1 mm. As a result, any conventional size telescope aperture (i.e., 0.5 m) contains $10^3 – 10^4$ speckle scales and there is negligible modulation. The same cannot be said for radar altimetry where one large antenna is used as the transmitter and the receiver. This maximizes speckle modulation because $d = \theta_t Z$ and only one speckle scale is contained in the receiver aperture. The result is near unity $SNR$, independent of the strength of the return signal. Degradation in either the temporal or spatial coherence of the radiation will also act to reduce the speckle modulation. In laser altimetry the multiple longitudinal (temporal) modes and sometimes multiple transverse (spatial) modes of the laser transmitter produce additional averaging.

Analysis of speckle fading has been developed in detail by Goodman [33]–[35]. A further treatment by Gardner [36], [4] puts speckle analysis in parametric form for analysis of laser altimeter systems. He computes the normalized variance $NVAR_s$ for speckle where

$$NVAR_s = \frac{1}{M_s M_t},$$

and $M_s$ and $M_t$ are respectively the spatial and temporal speckle correlation scale numbers averaged by the receiver aperture. The maximum modulation of unity, $NVAR_s = 1$, occurs only in diffraction-limited laser radars of equal transmitter and receiver aperture sizes where single mode lasers are used. Otherwise

$$M_s = 1 + (4 \rho_c^2),$$

and

$$M_t = (1 + B^{-2}(r_s^2 + \tau_s^2)^{-1/2}),$$

where

- $r$ = receiver aperture radius,
- $\rho_c$ = transmitter transverse spatial coherence length
- $\lambda = \lambda \theta_t$,
- $\theta_t$ = laser divergence,
- $\lambda$ = laser wavelength,
- $B$ = detector bandwidth,
- $r_s$ = laser source coherence time, and
- $\tau_s$ = laser pulse width.

These equations can be used to compute the magnitude of the speckle modulation for a particular laser source, laser altimeter instrument, and altimetry application.

Optical wavefront distortion caused by the refractive-index fluctuations associated with atmospheric turbulence leads to a number of potential problems for the general case of vertical laser beam propagation through the atmosphere. Chief among these problems is scintillation, the rapid modulation of laser beam irradiance. Narrow laser beams also suffer in general from beam wander and distortion as they propagate through turbulence. The particular geometry of laser altimetry, however, works to reduce all these effects to small levels. Beam wander and beam spreading on vertical propagation paths through the atmosphere are negligible for the mrad-scale beam divergences used in laser altimetry and are also negligible due to the large distances between the turbulence layers and the receiver aperture.

Scintillation for a downward propagating laser beam is very similar to that for the case of the familiar phenomena of stellar scintillation [37]. In both cases the optical wavefront is nearly a plane wave at the top of the atmosphere. Optical phase distortions in the upper atmosphere result in a fluctuating irradiance pattern at the earth’s surface. This pattern has a typical depth of modulation of 60 percent at
Atmospheric refractivity also produces a range bias or offset in the laser altimetry measurement. The range measured to the earth's surface from a space-based laser altimeter exceeds the actual range due to a slowing (propagating delay) of the optical pulse by the refractive-index of the atmosphere. The amount of this delay depends on meteorological conditions and is about 2.4 m at nadir for the two-way atmospheric path from space to sea-level and return. The delay is also an inverse function of wavelength. Hopfield [38] points out that the propagation delay is simply the integral over \( n - 1 \) along the propagation path where \( n \) is the local atmospheric refractive-index and is proportional to atmospheric density. For vertical observations the integral over atmospheric density is just the surface pressure. Thus at nadir the propagation delay is independent of surface temperature and temperature structure in the atmosphere. Abshine and Gardner [39] review the formulation for range correction to account for the propagation delay. It is given approximately by

\[
\Delta Z = 0.002357 (0.9650 + 0.0164/\lambda^2) P_e \tag{11}
\]

where \( \lambda \) is laser wavelength in microns, \( P_e \) is surface pressure in millibars, and \( \Delta Z \) is range correction in meters. At 0.5 \( \mu \)m wavelength \( \Delta Z \) is 2.46 m and decreases to 2.34 m at 1.0 \( \mu \)m. The derivative of (11) with respect to surface pressure yields a range correction sensitivity of 2.3 mm/mbar. Thus a 43 mbar uncertainty in \( P_e \) would result in a 10-cm range error. This illustrates that \( P_e \) must be known or modeled to about 2.5 percent in order to keep the uncertainty in atmospheric propagation delay to a low level.

IV. Examples of Laser Altimetry Data

An example of space-based laser altimeter data is presented in Fig. 9. These data from the APOLLO 17 mission [47] were acquired for the entire circumference of the Moon at a horizontal spacing of approximately one pulse every 32 km and a vertical resolution of 1 m. Despite the low duty cycle of measurement, these data and similar data from APOLLO 15 and 16 represent a significant technological achievement and provide substantial science benefits [1].

Aircraft-based laser altimetry provides high-resolution topographic profiling of earth-surface landforms for geological research. Data are typically acquired for horizontal baselines of 1–30 km, and require removal of aircraft motion. Four examples of topographic profiles acquired from a jet aircraft at a 3 km altitude above terrain are presented in Fig. 10. These data sets were acquired for desert, volcanic, and impact landforms in the western U.S. during 1986–1987 by a prototype of a space-based laser altimeter instrument package [40]. Aircraft speed was approximately 100 m/s, laser footprint size was 3 m, and the laser pulse repetition-rate was 15 Hz. Each data profile is a composite line of the 500–1500 individual range measurements recorded by the laser altimeter data system on-board the aircraft. Fig. 10(a) reveals the complex vertical structure of a field of sand dunes. Note the presence of several periodic oscillations that result from wind-blown sand dune formation. The volcanic buttes in Fig. 10(b) have different shapes which are indicative of their different compositions and exhibit side slopes as great as 30°. Profile data in Fig. 10(c) indicate the very rough terrain of the SP Lava Flow in northern Arizona. The Lava Flow is elevated some 15 m above the surrounding smooth terrain. Roughness of the Flow indicated by the jagged range profile was confirmed by laser pulse spreading measurements of 1–2 m rms and separate ground-based field survey data. The sloping range profile has been corrected for aircraft motion by use of vertical accelerometer data. The upward slope from left to right in the figure is a real effect produced by sloping terrain leading to the volcanic vent.

Fig. 10(d) is an east-to-west traverse of Meteor Crater in Arizona. The data show the characteristic shape of an impact crater and have meter or better vertical precision. Wall slopes on the west side of the Crater are as high as 60°, yet caused no loss of laser range data. The data in Fig. 11 are also a traverse of Meteor Crater and include the corresponding profiles of backscattered laser pulse amplitude and pulse spreading. The rms pulse spreading that is plotted is a combination of the laser pulse width, surface slope, and vertical roughness within the laser footprint. At the crater rim pulse amplitude increases by a factor of 1.5 and there

---

![Fig. 9. Circum-Lunar altimetry data acquired during the APOLLO 17 mission with the APOLLO Lunar Laser Altimeter from an orbital height of approximately 100 km [47].](image-url)
Fig. 10. Examples of aircraft-based laser altimetry data acquired from the NASA Wallops Flight Facility T-39 aircraft during the period 1986-1988 at an altitude of approximately 4 km [40].

Fig. 11. Laser altimetry data products for a traverse of Meteor Crater, AZ, acquired from the NASA Wallops Flight Facility T-39 aircraft during October 1986 at an altitude of 4 km.

is a small reduction in pulse spreading. Both effects are likely the result of the smooth, high-reflectance ejecta blanket for impact craters.

Fig. 12 is an example of aircraft laser altimetry data [41] on a profile transecting the California coast just south of Big Sur. In this case the laser altimeter instrument was a pulsed Nd:YAG system constructed for cloud lidar observations and operated on the NASA ER-2 aircraft in 1983. The significance of this data set is the 10 cm resolution in range measurement with over 1000 m change in surface topography as the aircraft flight track crossed the coastal mountain range. Over the ice sheets the same vertical resolution is required and total vertical excursions can reach several kilometers. During this laser profile the altimeter instrument maintained a high S/N measurement on each laser pulse as it constantly followed large excursions in the mean surface height. All data were acquired from an aircraft altitude of 20 km, beyond a significant portion of the earth’s atmosphere. The NASA ER-2 cloud lidar system that made these measurements is a forerunner of laser altimeters on space platforms by virtue of its autonomous operation, compact size, and ability to withstand reduced atmospheric pressure and wide variations in the thermal and vibration environment. This cloud lidar is functionally identical to the instrument required for ice-sheet measurements with the exception of no correction for platform pointing angles or position.

V. PROSPECTS FOR LASER ALTIMETRY IN SPACE

Laser altimeter instruments can make a contribution to the science of remote sensing in a variety of space-based applications. The role of a laser altimeter in lunar orbit to
measure topography is a particularly important example [43]. Understanding the global topography of the Moon is essential for answering questions concerning lunar origin and evolution. Some of these questions relate to the precise figure of the Moon, the nature of gravity anomalies, and the thermal and loading histories of major impact basins. Others are the styles and volumes of volcanic eruptions, measurements of modification processes, and problems associated with impact cratering. The correlation of lunar surface geochemical processes and topography requires further assessment. Finally, information necessary for the optimal placement of lunar bases will require accurate knowledge of the local relief of the lunar surface at the small scale sizes most appropriate for laser measurements [44].

Many of the same words describing laser altimetry science applications in lunar orbit can be used for an instrument in Mars orbit. Here there is strong justification, since less is known of Martian topography. Topographic data are required in preparation for the eventual deployment of rover vehicles and establishment of Martian bases.

Another major application is a laser altimeter in earth orbit. If this orbit is polar there are significant contributions that can be achieved in the high-resolution measurement of ice sheet topography, sea-ice distribution, landform topography, and cloud-top heights on a global basis. Ice and terrain topography can be measured at sub-meter vertical resolution and approximately 100 m horizontal separation with a 50-100 m diameter laser footprint. Ice and terrain roughness at tens-of-centimeter-scales can be measured via laser pulse waveform analysis. In geology the laser altimeter offers the possibility of studies of volcanic, erosional, and tectonic landforms on a global basis. Examples of study areas might include the Himalayas, Tibetan plateau, equatorial sand sheets, polar landforms, and coastal erosion zones. It should also be possible to study meteoric impact landforms in remote locations. Further details of the laser altimeter in earth science applications can be found in a series of recent publications [17], [19], [41], [43], [46].

When terrestrial observations are obscured by cloud cover the laser altimeter measurements of cloud-top height provide a very significant auxiliary data set for comparison with and interpretation of passive electro-optical and microwave radiometer data sets used to study the earth’s atmospheric processes. Although laser altimeter pulses are lengthened by at least an order-of-magnitude in reflection from the cloud-tops, the backscatter pulse should have sufficient intensity for coarse range and amplitude measurements. This application bridges the gap between short-pulse, high-resolution laser altimetry data and the longer-pulse, lower-resolution data of lidar measurements in the earth’s atmosphere.

ACKNOWLEDGMENT

The author is especially grateful for the use of the airborne laser altimeter data from missions led by J. Garvin and J. Spinhirne of the Goddard Space Flight Center.

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