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Challenges and Opportunities in Lidar Remote Sensing

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INTRODUCTION

Lidar (light detection and ranging, also LIDAR, LiDAR, and LADAR) advanced rapidly after the invention of the laser in 1960 (Maiman, 1960; Woodbury et al., 1961; Smullin and Fiocco, 1962; Schotland, 1966; Cooney, 1968; Melfi et al., 1969). A variety of lidar technologies have been developed to provide atmospheric and surface properties during the last 60 years (Fiocco and Smullin, 1963; Weitkamp, 2005; Kashani et al., 2015) to support advancements in digital models of terrain, cryospheric discovery, terrestrial ecology, hydrology, atmospheric science, and oceanography. The successful lidar operations of NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO, Winker et al., 2010) and Ice, Cloud, and land Elevation Satellite (ICESat, Markus et al., 2017) and ESA's Aeolus wind satellite (Kanitz et al., 2020) highlight a new era of lidar developments and applications. Measurement concepts and technology are evolving simultaneously in different directions. Doppler lidars with different measurement capabilities are widely adopted by the wind energy industry (Krishnamurthy et al., 2012; Bos et al., 2016). Miniaturization and photon-counting instruments are opening completely new areas in science and applications with cheaper ground–based instruments and ultra-light, affordable drones. 3D surface mapping by imaging lidar is required across a broad – spectrum of applications, from construction projects (Pu and Vosselman, 2009) to understand land – atmosphere interactions (Colin et al., 2010; Faivre et al., 2017). The higher performance achievable by a time-correlated single-photon counting implemented in a multiple beams system has been documented (see e.g. Chen et al., 2018). A growing range of terrestrial, unmanned aerial vehicle (UAV or 'drone') (González-Jorge et al., 2017) and airborne scanning systems is attracting a wide community of professionals to deploy such systems to support large engineering projects and to monitor in great detail infrastructures of all sorts, from bridges to buildings and urban canyons (Wang et al., 2013; Roca et al., 2016). The role of lidar will be increasingly important in the future. Although there are many potentials for new lidar technology advancements, lidar activities are gradually shifting from technology developments to applications. Thus, discussions here mainly focus on the opportunities and challenges for advancing lidar applications in the future.

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LOW COST AND TURNKEY ATMOSPHERIC LIDAR SYSTEMS TO SUPPORT OPERATIONAL APPLICATIONS

To support operational lidar applications, transferring research lidars into turnkey systems and reduce their costs are necessary steps. During the last 20 years, advances in industrial lasers improved lidar system reliability and lowered system development and operational cost. Recent wind energy developments accelerated the low cost and turnkey Doppler lidar developments. Now micropulse type lidars are available for routine aerosol and water vapor measurements (Welton et al., 2001). Compact Raman lidars were demonstrated for airborne and ground-based operations (Wu et al., 2016; Lange et al., 2019). However, we still need to overcome many issues . First, atmospheric lidar system designs have to consider providing quantitative and automatic or semi-automatic lidar data processing. Second, enhancing system stability has to be one of the high priorities. Micropulse lidar (MPL) is one of the successful lidar designs to support aerosol and cloud observations, and the DOE/ARM program operated MPLs for the last 20 years. However, temporal variations of MPL system performance, especially in near range alignment, makes it difficult to use long-term MPL data to provide consistent long-term aerosol products. Third, it is critical to consider improving near-surface (within 500 m) measurements for ground-based lidar system design. Due to incomplete overlapping between the transmitting and receiving optical system, near-surface measurements of aerosol, water vapor, and temperature are often unavailable or with large uncertainties. However, these near-surface measurements are critical for many applications. Future lidar systems with ceilometer's robustness and increased capabilities will enhance our atmospheric monitoring capabilities (Engelmann et al., 2016; Wu et al., 2016; Stillwell et al., 2020).

LIDAR NETWORKS TO SUPPORT RESEARCH AND OPERATIONS

The spatial variability of atmospheric properties and processes limits the values of single lidar measurements. Many existing lidar research networks, such as the European Aerosol Research Lidar Network (EARLINET, Pappalardo et al., 2014), the Asian Dust Network (AD-Net, Sugimoto et al., 2016), the National Aeronautics and Space Administration Micropulse lidar network (MPLNET, Welton et al., 2001), and the Network for the Detection of Atmospheric Composition Change (NDACC, De Mazière et al., 2018), were developed in the past with different success. For future operation supports, network lidar operations are critically needed (Bösenberg and Hoff, 2007; National Research Council, 2009; Wulfmeyer et al., 2015). Different-scale networks are needed to meet various application needs. Regional lidar networks can monitor urban air quality and cover the data gaps for weather models (Langford et al., 2018). A global lidar network is necessary to study stratospheric and mesospheric variations (Chu and Yu, 2017; De Mazière et al., 2018).

Robust and cost-effective lidar systems are essential to support long-term operational lidar networks in the future. Global ceilometer (a simple elastic lidar) network is the most successful lidar network to support operation so far. Current efforts in using ceilometer vertical profiles to characterize the Planetary Boundary Layer (PBL) structure will further empower the ceilometer network (Hicks et al., 2019). Lidar technologies for temperature, water vapor, and wind measurements, which are regarded as a high priority to fill observation gaps (especially within PBL) to improve weather and air quality prediction, are mature for operational lidar networks in the near future (Goldsmith et al., 1998; Nehrir et al., 2011; Reichardt et al., 2012; Weckwerth et al., 2016; Wu et al., 2016). Ocean-based lidar deployments, on buoys, island, ice, and commercial ships, are needed to fill critical measurement gaps (Mariage et al., 2017). To fully unleash the power of lidar network observations, the quality control, archive, and open access of lidar data will be essential.

LIDAR DATA ASSIMILATIONS TO IMPROVE WEATHER AND AIR QUALITY FORECAST

Lidar data can be used to improve weather and air quality forecast through data assimilations. Studies show that assimilating Doppler lidar wind measurements can improve not only short-time resource predictions of wind farmers (Würth et al., 2019; Perr-Sauer et al., 2020) but also mesoscale weather forecast (Pu et al., 2010; Kawabata et al., 2014). Assimilating Raman lidar water vapor and temperature measurements can fill current observation gaps in PBL to improve model performance (Wulfmeyer et al., 2006; Chipilski et al., 2019; Leuenberger et al., 2020).

While having operational lidar networks and maintaining high-quality data collections are necessary for operational data assimilations, further developments of assimilation methods to effectively use highly temporally and vertically resolved lidar measurements are still needed. Although it is straightforward to assimilate lidar water vapor, temperature, and wind measurements by adjusting corresponding model variables, fully using high temporal resolution observations requires further investigations. Assimilating lidar aerosol measurements can improve PM2.5 forecast (Cheng et al., 2019; El Amraoui et al., 2020). Using PBL structure information contained within aerosol vertical structures to refine model PBL representation, however, needs further explorations. Future reliable lidar data network measurements and advanced lidar data assimilation approaches will make high impacts on regional weather and air quality forecast.

MULTI-PARAMETER LIDAR MEASUREMENTS TO SUPPORT ATMOSPHERIC PROCESS STUDY

Supporting atmospheric process study has been one of the main lidar applications, but the values of individual atmospheric parameter measurements are limited now after knowledge gained from the past studies. Therefore, synergizing multiple lidar measurements is needed in the future. For air quality studies, multiwavelength elastic lidar measurements can provide aerosol size and type information. Vertical profiles of relative humidity and stability within the PBL from lidar water vapor and temperature measurements are needed to quantitatively interpret the observed variability in aerosol properties (Veselovskii et al., 2009).

Aerosol-cloud interaction is one of the primary sources of uncertainties in future climate predictions. Ground-based multiple lidar measurements are critical to untangle the puzzle. Aerosol size and composition from multiwavelength lidar, vertical wind from Doppler Lidar, water vapor and temperature from Raman lidar or DIAL, and droplet concentrations retrieved from lidar cloud extinction measurements help to understand aerosol-cloud interactions for low-level clouds under different dynamical and thermodynamical conditions. Such multi-lidar measurements are needed under different aerosol and cloud conditions over multiple locations to fully understand aerosol-cloud interactions. For cloud studies, lidar multiple scattering (MS) is still a challenging issue. MS contains cloud microphysical and optical information (Donovan et al., 2015). Further exploring MS information together with lidar depolarization measurements could increase lidar capabilities to observe optically thick clouds.

PBL processes are still poorly understood and represented (National Academics of Sciences, 2018a; National Academics of Sciences, 2018b). The Land-Atmosphere Feedback Experiment (LAFE) deployed several state-of-the-art lidars at the ARM Climate Research Facility Southern Great Plains Megasite (SGP) to study land-atmosphere feedback (Wulfmeyer et al., 2018). LAFE demonstrated the power of multi-lidar measurements for the PBL study by providing simultaneous water vapor, temperature, aerosol, wind, and turbulence profiles. Besides ground-based multi-lidar observations, airborne multi-lidar observations are essential for critical atmospheric process studies by sampling where processes are happening. Aircrafts carrying lidars and radars can track a fast-moving storm to observe dynamical interactions (Liu et al., 2019). Compared with operational lidar applications, supporting atmospheric process study requires more powerful lidars to provide accurate measurements at fine temporal and spatial resolutions (Behrendt et al., 2015; Hammann et al., 2015; Lange et al., 2019).

SYNERGIZING LIDAR WITH OTHER REMOTE SENSORS FOR ATMOSPHERIC CHARACTERIZATIONS

Combining lidar with other active and passive sensor measurements offer new observational capabilities. Currently, lidar measurements are widely combined with cloud radar and radiometer measurements for cloud macro- and microphysical properties characterizations (Stephens et al., 2002; Wang and Sassen, 2002; Delanoë and Hogan, 2008; Deng et al., 2010; Wang et al., 2012). Synergizing lidar with other sensor measurements could advance atmospheric observation capabilities in many other frontiers (Nehrir et al., 2017). Although ground-based Raman and DIAL lidars can provide reliable vertical resolved water vapor and temperature profiles, these measurements are limited to below clouds when low or middle-level clouds are presented due to strong cloud attenuation (Turner et al., 2000). On the other hand, microwave radiometer profiler can provide all-weather measurements, but with coarse vertical resolutions (Zhang et al., 2018). Combining Raman/DIAL lidar and microwave radiometer profiler measurements could offer improved all-weather water vapor and temperature profiling capabilities with multi-sensor optimization retrieval approaches (Turner and Blumberg, 2019). Similarly, the synergy of Doppler lidar and cloud radar measurements could offer in and out cloud wind fields to support many critical studies, such as cloud and environment interactions, especially combined with measurements from other types of lidars (Turk et al., 2020).

LIDAR SYSTEMS FOR OCEAN MEASUREMENTS

Oceans control the weather and climate globally and are poorly observed. Satellite ocean color measurements from passive visible sensors have provided a sustained synoptic view of the distribution of ocean optical properties and biogeochemical parameters, but lacking vertical information within the water column. Microwave and IR ocean observations from space only offer ocean surface properties due to strong water absorptions. Airborne lidars (Hoge and Swift, 1981; Churnside, 2014) have been used to study ocean subsurface properties for decades. CALIOP measurements demonstrated that space-borne elastic lidar signals could provide depth-resolved values of plankton properties globally (Lu et al., 2016). However, extract ocean particle information from elastic-only measurements is still challenging (Schulien et al., 2017). Ocean-optimized space lidars synergized with other ocean measurements (Hostetler et al., 2018; Chen et al., 2019; Jamet et al., 2019) would transform our ocean measurement capability. Further advancing lidar measurements with Brillouin scattering, Raman scattering, and fluorescence signals could provide ocean mixing layer temperatures, salinity, other chemical component information simultaneously, at least from airborne platforms (Hoge et al., 2005; de Lima Ribeiro et al., 2019).

MULTI-SPECTRAL SURFACE AND VEGETATION MEASUREMENTS

Multi – spectral lidar systems are expected to fill a major gap in land science by capturing at the same time two essential features: the 3D geometry of land targets and the type of observed surface through the spectral information. Morsy et al., (2017) demonstrated that the combination of building height and spectral information achieved a clearly higher accuracy than elevation data alone in mapping urban land cover. Retrieval of bathymetry using a single spectral channel is a well – established lidar application but opportunities for innovations remain significant, such as the integration of mono-spectral lidar with passive multi-spectral images to map coastal water (Zhang et al., 2019). Imaging, multi-spectral lidars combine differential water absorption with range measurements to map coastal waters and the land/water boundary very accurately (Morsy et al., 2018)

SPACE-BASED LIDAR FOR MEASUREMENTS BEYOND AEROSOL, CLOUDS, AND SURFACE HEIGHT

Lidar measurements from CALIPSO, CATS, and ICESat satellites transformed our view of global aerosol, cloud, and ice sheet distributions (Winker et al. 2010; McGill et al. 2015; Yorks et al., 2016; Markus et al., 2017; Neumann et al., 2018; Neuenschwander and Pitts, 2019; Neumann et al., 2019). The latest NASA Earth science decadal survey recommends several missions requiring lidars to meet the science measurement objectives (National Academics of Sciences, 2018a). Global measurements of tropospheric wind, water vapor, CO2, temperature, and surface vegetation from space lidars will be highly desired (Baker et al., 2014; National Academics of Sciences, 2018a; National Academics of Sciences, 2018b), but there are challenges to overcome. ESA's Aeolus wind satellite was launched on August 22, 2018 and demonstrated the feasibility to measure wind from the space (Kanitz et al., 2020). Its fixed-beam pointing cannot provide wind speed and direction, however. Further technological advancements are needed to provide wind speed and direction measurements to better constrain weather models. DIAL lidars for water vapor and CO2 from space require high power lasers with stable narrow-line output, which are under development. Raman lidar is the only feasible lidar technique to provide fine vertical-resolved temperature profiles from space, but it requires high pulse energy 355 nm lasers with above 50 W power (Di Girolamo et al., 2018). There are multiple challenges in developing and operating such high energy UV lasers for a space-borne lidar. Lessons learned from Aeolus and EARTHCARE UV lidars should help future space-based Raman lidar development. NASA's PBL and Surface Topography and Vegetation (STV) incubation programs will accelerate future space-based new lidar developments. Although needs are different for different types of space-based lidars, developing high electrical-to-optical efficiency lasers and low-weight large telescope will benefit all space-based lidar applications.

MINIATURIZATION AND PHOTON-COUNTING SURFACE LIDAR SYSTEMS

The promise of photon–counting LIDAR is to deliver similar performance as traditional waveform – sampling systems at significantly reduced mass and power consumption. This may lead to a host of new applications, made feasible by far – reaching miniaturization, but requires a fundamentally different approach to data processing and analysis. Three-dimensional point clouds are widely used across a wide spectrum of applications from construction projects to forestry. Time-correlated single-photon counting (TCSPC) is a very active area of technological development. Multiple beam systems can improve substantially the accuracy of time-of-flight ranging and three-dimensional (3D) imaging, as demonstrated by Chen et al., (2018).

BIOSPHERIC, CRYOSPHERIC AND HYDROLOGIC PROCESSES

Multiple–beams and scanning systems are increasingly providing the measurements necessary to capture biospheric, cryospheric and hydrologic processes. Detailed 3D measurements of terrestrial vegetation over space and time are necessary but very scarce, thus making progress very hard in our understanding of the role of vegetation in the Earth System, particularly in the carbon and water cycle. It is not only the amount of vegetation that is of importance, but it is the detailed 3D structure of vegetation canopies (Menenti and Ritchie, 1994; Næsset, 1997; Straatsma and Baptist, 2008; Wang et al., 2009; Bucksch et al., 2014) to determine radiative and convective exchanges with the PBL (Faivre et al., 2017). Water – related morphometric features can be extracted from point – clouds generated by imaging lidars (see e.g. Koenders at al., 2014).

Notwithstanding its short life and sparse spatial coverage, the data acquired by GLAS on ICESat–1 have boosted unprecedented advances in understanding the response of alpine glaciers to climate forcing. The challenge ahead is to bring to fruition the far better capabilities of ATLAS on ICESat–2, while at the same time capturing the surface structure at a detail sufficient to understand mass transport within a glacier.

Accurate measurements of water level deliver unique global information on water storage and flow, thus filling a major gap in the observation of the terrestrial water cycle. LIDAR measurements of water level from space are inherently sparse in space and time, thus requiring innovative approaches to bring such information to fruition (Phan et al., 2012).

INFRASTRUCTURE SURVEYS

Monitoring and assessment of very diverse infrastructures require short – range LIDAR measurements at high accuracy and density (see e.g. Olsen et al., 2010), which leads to merge multiple point – clouds acquired by terrestrial laser systems or very large point-clouds acquired by a moving and unstable platform (e.g. UAV). Developing efficient and accurate ways to create such large data sets while minimizing the degradation in data quality remains a very active area of research.

In structural engineering, accuracy required for change detection (or deformation measurement) or 3D object reconstruction is often sub-millimeter, generally about 5 mm or less. This requirement cannot always be met by the accuracy of the laser scanning point cloud from a single scan, and the accuracy of the point cloud from multiple scans is even worse. Moreover, removal of outliers and mixed pixels are also critical issues in identifying the real surface of an object. This is a major challenge in 3D object reconstruction. To meet this challenge a combination of solutions is needed, from technological developments in laser scanning to experimental protocols, passing through high performance data processing, especially for aligning large point clouds from multiple scans.

URBAN LANDSCAPE AND ENVIRONMENT

Generation of 3D models of urban space is by now a mainstream application of scanning LIDAR systems (Pu and Vosselman, 2009; Vosselman and Maas, 2010), but there is a clear trend towards the accurate representation of ever-increasing details within the built-up space, such as individual trees and signposts (Wang et al., 2017). This requires automatic recognition of objects, in addition to their very accurate and detailed representation. The challenge here is technological evolution towards miniaturization and autonomous data processing and concurrent advances in algorithms and their fundamentals. Recent UAV platforms jointly collect imagery and lidar data. Acquired 3D point clouds may achieve accuracies and resolutions of some millimeters, so far limited to terrestrial data capture. Further benefits of combined processing result from adding lidar range measurement to multi-view-stereo image matching during the generation of high-precision dense 3D point clouds.

A majority of the human population lives in urban and suburban areas. With increasing urbanization, urban meteorology and air quality have become an emerging area of great interest. How the properties of urban environments modify the PBL structure and impact urban weather and air quality is a largely unresolved question (National Research Council, 2012). There remain numerous scientific, technical and computational challenges to improving urban weather and air quality forecasting. Understanding urban PBL properties and processes is crucial. Over urban street canyons, characterized by different scale inhomogeneities regarding the surface type and terrain height, modern understanding of PBL physics and parameterization is not sufficient for urban applications (Kukkonen et al., 2012; Zhang et al., 2012). Although there are various ways to provide near-surface observations, these are not sufficient in identifying and quantifying the physical processes that drive the urban PBL (Muller et al., 2013). The upper 90% of the urban boundary layer remains under-researched (Barlow, 2014). Regional lidar networks with multi-type lidar systems could fill the data gap to enhance urban PBL process studies and improve urban environment predication.

SUMMARY

Future lidar applications can go beyond the traditional fields discussed above. Short-range 2-D/3-D lidar advanced rapidly driven by autonomous vehicle development needs. Further developments of all-fiber lidar could provide a reliable and cost-effective way to detect turbulence, wind shear, volcanic ash, supercooled liquid clouds with icing risks, and high ice water content clouds from aircraft in real-time to support safe aircraft operations (Schmitt, 2017; Thobois et al., 2019). If we successfully meet these challenges, lidar measurements from ground, aircraft, and satellite will continuously transform our capability to support earth system science study and power new lidar applications.

AUTHOR CONTRIBUTIONS

ZW and MM work collaboratively on this grand challenge paper in lidar sensing.

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