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Laser remote sensing: yesterday, today and tomorrow

Обсуждается развитие методов дистанционного зондирования атмосферы. Продемонстрированы примеры лидаров, основанных на эффекте комбинационного рассеяния, для дистанционного обнаружения и мониторинга загрязнения, а также для изучения динамики различных компонент и их параметров. Когерентный лазерный локатор открыл возможность дистанционного измерения скорости объектов и сред, представляя собой жизненно важный источник информации для определения градиента скорости ветра и обеспечения безопасности полетов. Перспективным направлением развития лазерной локации является включение данных о дальности и скорости в двухмерное изображение сцены. Стробирование по дальности как метод построения трехмерного изображения (наблюдение через рассеивающую среду, лиственный покров, одежду, и т.д.) является перспективным направлением для военных и гражданских применений.

Development of laser remote sensing (lidar techniques) is discussed for atmosphere and ocean investigation. Examples of Raman lidars based on vibrational and rotational energy states of molecular species are demonstrated for remote detection and monitoring of pollution, as well as for studies of dynamics of different components and their parameters. Coherent laser radars allowed remote measurement of speed and vibrations, Doppler velocity information being crucial for the solution of the problem of windshear detection and flight security. A promising trend in laser radar development is incorporation of range and velocity data into the image information. Gated imaging, as one of the 3D techniques, demonstrated its prospects (looking through scattering media, vegetation, dress, etc.) for military and civilian use.

Ключевые слова: *дистанционное зондирование, лазерный локатор, измерение параметров рассеивающих сред, лазерная дальнометрия, визуализация вибраций.*

Introduction

Born as a younger brother of microwave radar, laser radar was thought to have bright future delivering higher spatial resolution and higher accuracy in the same applications with the microwave radar. Giant efforts and huge expenses were the cost to build monster prototypes with the near to hundred meters long optical train to achieve these illusive goals. In its development, laser radar was choosing its own ways, sometimes still sharing the ideas with its older brother.

During the late 60’s and early 70’s, military research laboratories and industry began developing laser systems for range finding, proximity fuzes and weapon guidance. The early lasers used ruby as the lasing medium at the cost of poor efficiency, eye safety issues and non-covertness. The former Soviet Union was leading numerous works with wide range of applications. Publications included fundamental books on the theory of laser radars [1,2,3], as well as on the engineering problems [4,5]. Some ideas about the technology level in the field of laser radar of those times can give a later publication [6]. One of the first Soviet laser range finders BD-1 was described in the book published by SPIE [7]. Rich military heritage in development of range finders created at the Polyus Institute and converted into the range finders for civilian purposes can be found at the Polyus website [8]. The technology of laser range finders and laser designators matured and can be represented by numerous operational instruments described in the Encyclopedia [9]. They are installed on helicopters and on well known Soviet/Russian airplanes of Su and MiG series.

The initial laser-to-target-and-return time-of-flight experiments were made by NASA in the mid-1960's. The first long-distance laser ranging was implemented in 1969 using a retroreflector positioned on the Moon by the Apollo 11 astronauts. Additional retroreflector packages were landed on the lunar surface during the Apollo 14 and Apollo 15 missions. Two French-built retroreflector packages were soft-landed on the lunar surface by Soviet landers. This article is an extension of our recent presentation to the SPIE Conference on Laser Radar Technology and Applications [10] with specific attention to the problems of remote sensing.

1. Environmental lidars

In parallel to the military laser sensing, the research community studied lidar for atmospheric and ocean sensing. For example, lidar observations of the mesosphere were made using a ruby laser as early as 1963 [11]. In the US, vertical water vapor distribution was studied [12] using a temperature tuned ruby laser, it was the first experiment on DIAL (differential absorption lidar). In the FSU, the atmosphere temperature was studied by Arshinov et al. [13]. Laser sensing of the humidity profile of the atmosphere was studied by Zuev et al. [14]. Fundamental achievements in investigation of the ocean, that include laser remote sensing, are described in monograph of Ivanov [15]. Limited space in this paper does not allow us to go deeper into the atmospheric and ocean lidar development and we refer to the textbooks and reviews for further reading [16,17]. Examples of lidars developed in Sweden and the FSU are shown in Fig. 1 [18,19].

Development of Raman lidar [20,21] enabled measurements of the optical and meteorological properties of the atmosphere based upon vibrational and rotational energy states of molecular species: water vapor and ozone, temperature, optical extinction, optical backscatter, multi-wavelength extinction, extinction/backscatter ratio, aerosol layers and cloud formation/dissipation (see examples in Fig. 2). Angular scattering technique replenishes the information due to measurement of the scattering phase function for aerosols including the polarization ratio of the scattering phase function, number density versus size, size distribution, identification of multi-component aerosols, index of refraction, etc. Multistatic aerosol lidar and multi-wavelength multistatic lidars are good candidates for prospective studies.

One of the vitally important functions aboard a plane is warning about a windshear that can result in plane crash, especially during takeoff and landing (Fig. 3). When landing, a plane enters a microburst encountering the variation of the airspeed. An example of wind velocity distribution in the windshear cross-section measured with laser radar [22] is given in Fig. 4.

After the headwind, a downdraft and a tailwind follow, rapidly reducing the climb potential. This condition can cause plane to crash. Onboard warning system, with 15 to 40-second warning will allow pilot to deal with this hazard. That is one of the important reasons of a special attention paid to lidar systems for wind measurements.

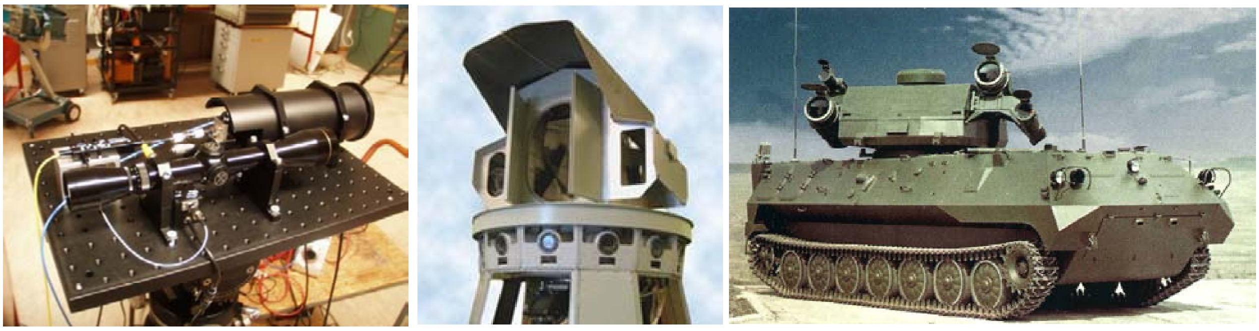

Fig. 1. Lidars for atmosphere investigation (from left to right): All-fiber coherent multifunctional CW ladar for range, speed, vibration, and wind measurements at 1.55 μm (FOI, 2000); Lidar automatic system for remote air pollution monitoring in large industrial areas (Institute of Precision Instrumentation, Moscow); Laser system КДХР-1Н ("Даль") for remote chemical agents detection (Astrofizika Corp., Moscow)

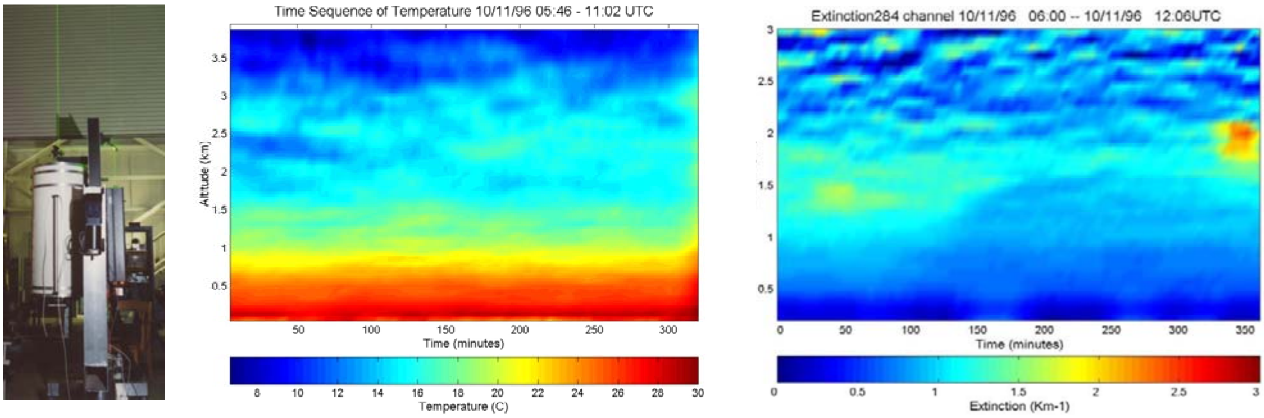

Fig. 2. Lidar at the Pennsylvania State University (left) and dynamics of temperature and extinction (right)

Fig. 3. Outline of the effect of windshear

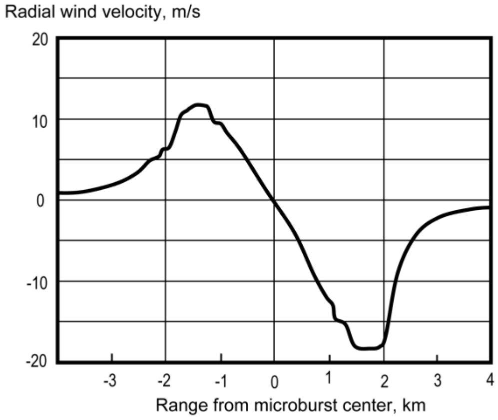

Fig. 4. Velocity distribution within the windshear

The task can be solved with coherent lidar that makes use of spatial and temporal coherence properties of laser radiation. By mixing the scattered light field with an optical local oscillator beam, the full phase, frequency and amplitude information in the signal is made available. In addition, shot noise in the local oscillator beam may be used to dominate thermal noise in the detector to provide quantum-limited detection of the signal beam [23]. For effective operation, very precise control of laser parameters is required together with profound understanding of optical arrangements, scattering mechanisms, propagation, signal processing, etc.

Wind sensing is an effective application for coherent ladars. Measurements included various ground-based programs, including local wind field measurement and wake vortex investigation at airfields. Airborne systems were used to investigate avionics problems of true airspeed, pressure error, windshear warning and collection of atmospheric backscattering over the North and South Atlantic. The problems of correlation methods of wind velocity measurement were studied by Matvienko and Samokhvalov [24]. In 90’s, the European Space Energy has supported studies and technology development for a space-borne wind lidar in the Atmospheric Laser Doppler Instrument (ALADIN) program. Pioneering wind lidar work in Europe was performed at RSRE (UK), DLR (Germany) and at the Laboratoire de Meteorologie Dynamique, Ecole Polytechnique (France). For a review on early coherent laser radar work in Europe we refer to the paper by Vaughan, et al. [25].

Coherent laser radars have the potential of adopting similar methods as in microwave radar to Doppler sensing and combining this information with range finding. For sensing the windshear (Fig. 5), dual-beam coherent system is used [26]. A range of developed wind sensors is shown in Fig. 6 [27].

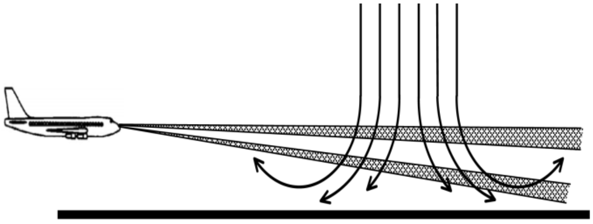

Fig. 5. Dual-beam windshear sensing

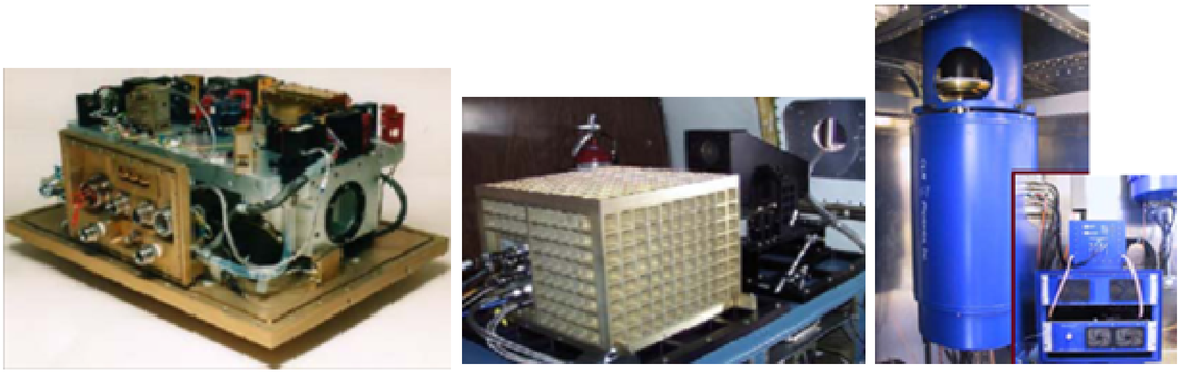

Fig. 6. Recent development of wind sensors (from left to right): NASA optical air turbulence sensor (2 μm, 1 mJ, 1 kHz, 5 cm aperture, chiller); NASA ACLAIM turbulence warning (2 μm, 8-10 mJ, 100 Hz, 10 cm aperture, chiller); MAG-1A WindTracer (2 μm, 2 mJ, 500 Hz, 10 cm aperture, heat exchanger)

One of the interesting concepts uses the frequency-modulated CW (FMCW) signal. The laser is a few watts in output power and is modulated by an acousto-optic modulator generating "chirp" pulses of the type familiar in microwave radar [28]. The method is described in detail in the monograph [29].

2. Imaging laser radars

Imaging laser radars are usually referred to as systems which scan or illuminate a limited field of view to obtain image information of distant objects in the form of reflectivity, spectral parameters, polarization, Doppler shift, 3D data. Military and security applications include target recognition and positioning, tracking, weapon guidance. Laser imaging with multiple military specified prototype systems is a rapidly developing field. However, the number of operational systems is limited. The technology for tactical use is based mainly on the range gated imaging.

One of the fascinating potentials with 3D ladars is the “look-through capability”, be it through camouflage, vegetation, fires, smoke or turbid water. The DARPA Jigsaw program supports the development of a 3D imaging laser radar technology and systems which can be used in airborne platforms to image and identify military ground vehicles hiding under camouflage or foliage. A pioneering work in Doppler imaging and especially “vibration imaging” that visualizes spatially resolved vibration signatures of vehicles is illustrated in Fig. 7.

Important contribution to laser radar imaging was made by MIT Lincoln Laboratory (LL) [30]. Examples of images from LL are shown in Fig. 8. The left one is a CO_2 (10.59 μm) laser-radar image of a bridge in which the range to each picture element is coded in color. The data collected in the original oblique view are transformed into an overhead view, as shown in the inset image. This view may be useful for missile seekers that use terrain features for targeting. The next, Doppler-velocity image was collected by the truck-transportable CO_2 laser radar. The Doppler shift of

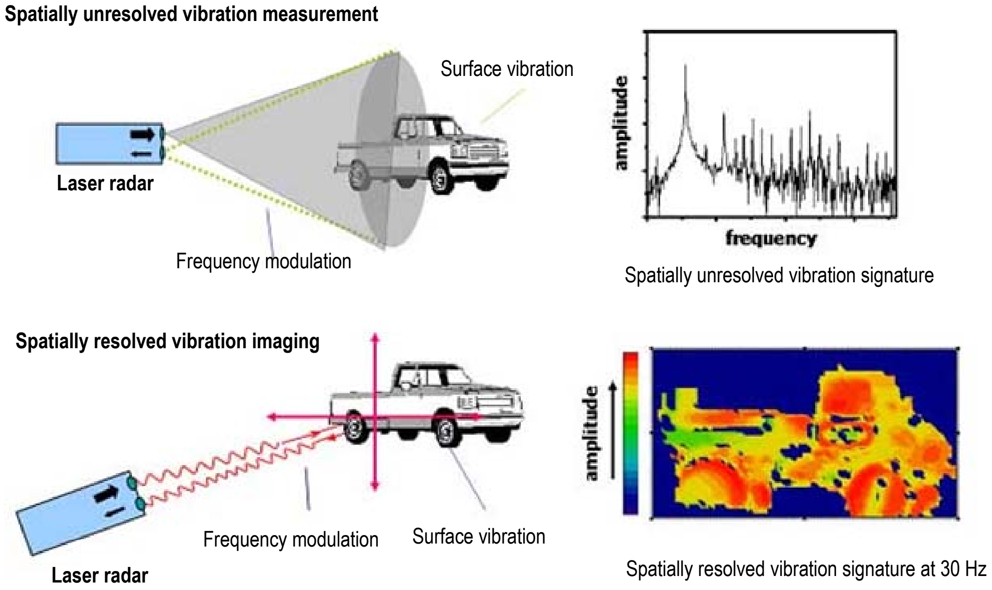

Fig. 7. Micro-Doppler imaging and sensing. Above: the conventional broad illumination vibration sensing; below: spatially resolved vibration sensing using a scanning coherent ladar

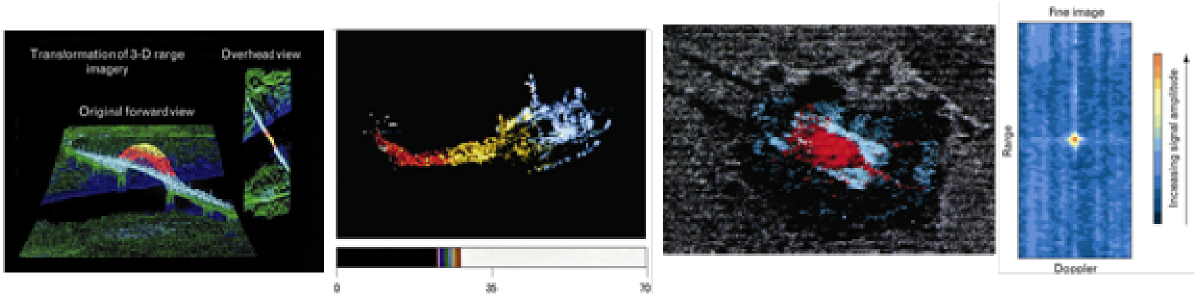

Fig. 8. Images from MIT/LL laser radar systems (from left to right): CO_2 laser-radar images of a bridge; Doppler-velocity image of a UH-1 helicopter executing a rotational maneuver; laser-radar angle-angle-range image of a tank concealed by a camouflage net; range-Doppler image of the LAGEOS satellite collected by the wideband CO_2 laser radar at Firepond

each of the approximately 16,000 pixels in the image was extracted by a surface acoustic-wave processor at a frame rate of 1 Hz. Velocity is mapped into color. The ability to sense moving parts on a vehicle provides a powerful means to discriminate targets from clutter. Still the next image made with a GaAs (0.85 μm) laser-radar is an angle-angle-range image of a tank concealed by a camouflage net. The laser radar utilizes a high-accuracy, sinusoidal, amplitude-modulated waveform while observing the tank in a down-looking scenario. The camouflage net was readily gated out of the image to leave the tank image. The right-edge image is a range-Doppler image of the LAGEOS satellite collected by the wideband CO_2 laser radar. This image was made with a bandwidth of 1 GHz. Doppler velocity resolution is approximately 30 cm/s. Color in the image represents relative signal amplitude.

Much of the imaging ladar research today is centered on flash imaging, that avoids scanning due to illumination of the sensor FOV with one or small number of short pulses to obtain 2D or full 3D images. The technology is so far based mainly on range-gated imaging (Fig. 9). The application appears to be targeting, i.e., the recognition of targets at longer ranges than what a cooperating IR camera can provide, thus enabling longer stand-off range for weapon release.

ASC (Advanced Scientific Concepts) has developed a FLASH 3D lidar video camera [31], a third generation of the FLASH system. It contains a 128×128 array with a ROIC (Read Out and Integration Circuit) capable of storing an image every 0.5 ns. The ROIC captures 20 time lapsed images for each pulse. These time lapsed images are then used to calculate the range estimates of the target area. Laser flashlamp is pumped by Nd:YAG, 1.57 μm, 50 mJ, 6.7 ns, 30 Hz. Time slices/frame are 20; time per slice 2.2 ns.

Selex developes advanced infrared detectors for multimode active and passive imaging applications including one detector that can be electronically switched from a thermal imaging function to a laser gated imaging function so that passive thermal imaging, solar imaging and laser-gated imaging can be designed into one electro-optic system [32]. The wavelength sensitivity of these detectors (APD arrays in HgCdTe) ranges from 1 μm to 4.5 μm which is promising for active multispectral imaging in the SWIR and MWIR regions.

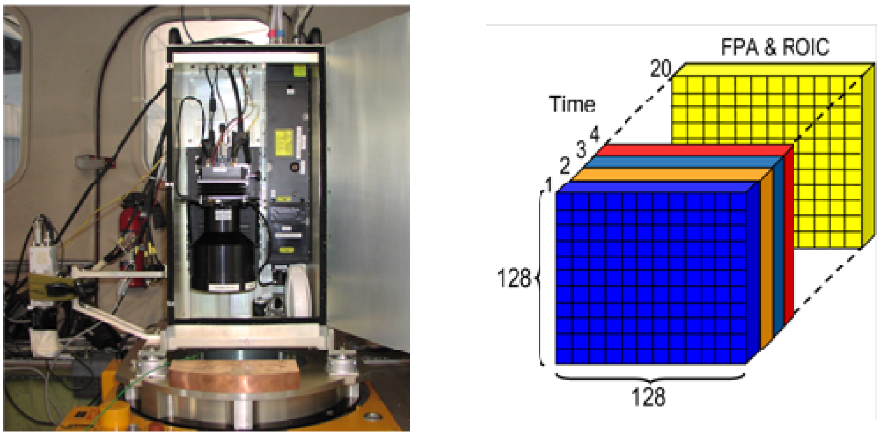

Fig. 9. Airborne flash ladar system (Northrop Grumman Aerospace Systems, 2010)

Conclusion

Laser remote sensing using the laser radars have passed through an impressive development stages since the first attempts to use lasers for distance measurement which resulted in broad military applications not only in range finding but also in weapon guidance especially by laser designation. Further studies led to development of laser imaging systems based on gated viewing and 3D imaging which are in the process of going to be fielded. Imaging systems are under intensive development including higher range resolution, new capabilities for better weather penetration, capabilities to look through vegetation, through clothes, through dense media, for target recognition. To-be-developed coherent focal plane arrays will measure target Doppler macro-velocity and micro-vibration in near-real time. Lasers can be used to "fingerprint" substances at a distance. This would include remote analysis and tracking of battlefield aerosols, man-made and natural agents. Wind lidar will also find applications at the military tactical level.

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