Measuring Atmospheric Scattering in 3D

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Abstract: To sense the volumetric distribution and microphysics of aerosols and cloud droplets in the 3D atmosphere, we develop passive multi-view scattering tomography. It uses a camera network or spaceborne views, augmented by Lidar. © 2018 The Author(s)

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Aerosols affect climate, health and aviation. Clouds create local effects such as precipitation, shadows on solar facilities, as well as strong climate effects. The roles of aerosols and clouds in Earth's radiation balance suffer from significant model uncertainties. It is important thus to sense and quantify the spatial and microphysical natural distributions of these light scatterers. The natural atmosphere is thus embedded with three dimensional (3D) volumetric distributions of scatterers of interest. However, for decades, remote retrieval of these scatterers has been based on assumptions of a plane-parallel atmosphere, solely vertical radiative transfer, and laterally independent yet wide regions.

We seek to part ways from these assumptions, and head for estimating scatterers as they really are: 3D distributions interconnected by 3D radiative transfer. The traditional, simplified assumptions had been a necessity while computing resources were scarce. As computers have become stronger, we may aim for 3D retrieval. In addition to computing power, several components are needed, which we address:
{1} Imaging configurations whose raw output data are sensitive to 3D volumetric content in the atmosphere.
{2} Practical setups in accordance to {1}, leading to empirical data.
{3} Computationally efficient 3D retrieval algorithms using data captured by {2}.
{4} Validation of retrievals obtained in {3}, using independent sources.

In medical computed tomography (CT), 3D volumetric content is sensed by a multiview system, in which the object is projected to multiple directions. We pursue an analogous concept: imaging a 3D atmospheric domain from multiple directions, and then using the multi-view data in a tomographic retrieval. This calls for wide angle integral imaging of the sky on a very large scale. Integral imaging can use a large array of cameras that are distributed on the ground [1,2] widely (to capture the large domain) and densely (to obtain many viewpoints for tomography), as illustrated in Fig. 1. Alternatively, multiple views of the domain can be obtained by satellites or aircraft [3,4].

There are however critical differences relative to medical CT. Due to the large atmospheric domain involved, it would be difficult for controlled lighting to provide sufficient intensity across the domain in a reasonable acquisition time. Thus, tomography must be passive: we rely on sunlight. Sun radiation cannot be moved or modulated over the domain, contrary to sources of medical CT. As a result, our atmospheric tomography relies on off-axis scattering, including multiple scattering. The image formation model is 3D radiative transfer. Tomographic reconstruction of

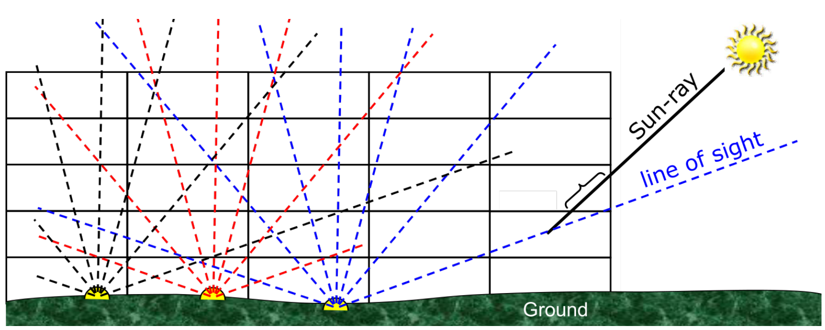

Fig. 1: Multiview imaging through a volumetric distribution in the atmosphere, using a ground camera network [1].

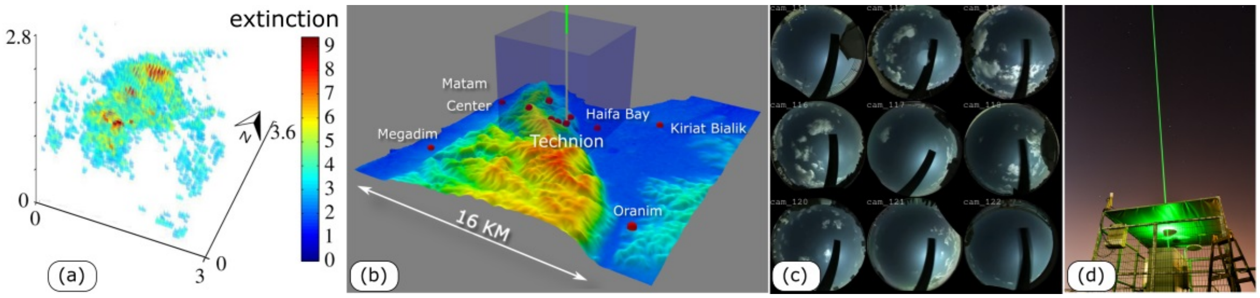

Fig. 2: [a] Recovered volumetric extinction eld from AirMSPI measurements [3]. [b] Layout of our system around the Technion campus. [c] Some of the simultaneous views taken by the camera network. [d] TROPOS Polly^{XT} mounted in the Technion (image courtesy of Nitzan Zohar)

atmospheric scattering thus become an inversion of the scattering forward-model. This inversion is done using optimization methods, run over a model-fit cost. We derive a closed-form gradient of the this cost, as a function of the unknown scattering density per voxel, when single scattering is dominant [1], leading to very fast retrieval. When multiple scattering is significant, there is a computational bottleneck when attempting large scale recovery. Thus in Refs. [2–4], steps are taken to make multi-scattering tomography tractable, without approximating the scattering order or angle range.

For data acquisition, we first performed an experiment using the Air-MSPI system of JPL, flown by NASA's ER-2. Tomographic recovery of a cloud, detailed in Refs. [3], is shown in Fig. 2a. It shows feasibility for multi-view cloud tomography from high altitude, which is a step towards spaceborne imaging. However, in this system, multiview images are taken sequentially, and there is no ground-truth for validation.

Hence, we develop a wide, dense, scalable network of solar-powered untethered wide-angle cameras looking upwards, which upload their data to The Cloud (internet) [5]. We set such a network around the Technion campus in Haifa, Israel. With such a system we obtain 3D shape recovery of clouds) [5], in high spatio-temporal resolution. The shape recovery constrains tomographic recovery to fewer unknowns. Tomography of aerosols benefits from estimate of their phase function. This can be obtained by a Cimel sunphotometer (CSPHOT). This is a multi-channel, automatic multispectral sun-and-sky scanning radiometer. It is an AERONET (AErosol RObotic NETwork) station in the middle of our experimental camera network.

For validation, we opt for an independent source at the center of our experimental network: the portable lidar system Polly^{XT} [6] by TROPOS. It measures the aerosol optical properties along a vertical profile in the middle of the atmospheric domain which we image. It also measures cloud-base height. The system will verify that 3D tomographic recovery results are consistent along the ray that the lidar samples.

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