Optical Tomography of Clouds and Atmospheric Turbulence from Space and Ground-based Cameras

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Abstract: Novel tomographic principles yield 3D atmospheric fields using multi-view imagery. Turbulence strength is mapped by observing scintillation of bulbs. Extinction in clouds is mapped volumetrically from polarimetric cameras onboard a satellite formation.

1. Tomography by scintillation and scattering

Clouds and turbulence are complex and critical processes in atmospheric and climate dynamics. However, currently, they are not mapped in three dimensions on large scales. There is a need to create methods for sensing these spatially varying complex structures, volumetrically. Due to the large areas involved, a practical way to achieve such mapping is by passive sensing, using radiation that exists anyway in the scene. Thus, we derive tomographic methods based on multi-view passive imaging. We test these methods outdoors.

Turbulence randomly changes the refractive index. As a result, distant light sources, such as street lights, appear to flicker. They project a scintillation signal. The *scintillation index* is measured empirically over a short time, using statistics gleaned from video data. The intensity observed at time t is $I(t)$. Its expectation value is $\langle I(t)\rangle_t$. The scintillation index is unit-less, defined by

$$\sigma_{\rm I}^2 = \left\langle \left[\frac{I - \langle I(t)\rangle_t}{\langle I(t)\rangle_t}\right]^2 \right\rangle_t = \frac{\langle I^2(t)\rangle_t - [\langle I(t)\rangle_t]^2}{[\langle I(t)\rangle_t]^2} = \frac{\langle I^2(t)\rangle_t}{[\langle I(t)\rangle_t]^2} - 1 \; . \tag{1}$$

Its value depends on the turbulence statistics, specifically the turbulence strength, C_n^2. The turbulence strength changes as a function of location $\mathbf{X}$, however. How can $C_n^2[\mathbf{X}]$ thus be mapped volumetrically? For wavelength λ, the value of $\sigma_{\rm I}^2$ corresponding to a line of sight (LOS) is

$$\sigma_{\rm I}^2 = 2.24 \left(\frac{2\pi}{\lambda}\right)^{7/6} \int_0^L C_n^2[\mathbf{X}(z)]\,(L-z)^{5/6} \left(\frac{z}{L}\right)^{5/6} dz, \qquad \mathbf{X} \in \text{LOS} \; . \tag{2}$$

This model holds, because bulbs are point sources, embedded - as the entire LOS - inside the atmosphere. Being a line integral, $\sigma_{\rm I}^2$ does not resolve the distribution of C_n^2 along an LOS. However, we place multiple video cameras in a field, observing the same region from multiple directions. They provide a large number of linear equations that relate the unknown field $C_n^2[\mathbf{X}]$ to multi-view scintillation data. This creates a new principle for linear tomography: that of turbulence strength by point sources [1], where cameras and sources are embedded in the medium. We demonstrated this principle [1] in an outdoor experiment (See Fig. 1).

Such a setup requires a set cameras operating in a large field (county scale) simultaneously. The cameras need to be calibrated geometrically and be radiometrically linear. This was achieved following experience obtained by a prior camera network [2], which we fielded in the same region. That camera network, which was also calibrated, operated autonomously. Each camera was untethered: it had solar power and cellular communication.

The cameras network in Ref. [2] obtained multi-view data for a new type of tomography: recovering volumetrically the extinction coefficient of clouds. For this task, the image formation model does *not* follow a linear model, contrary to typical medical tomography. In this case, the forward model is based almost only on scattered light, which makes the tomographic problem nonlinear in the unknowns.

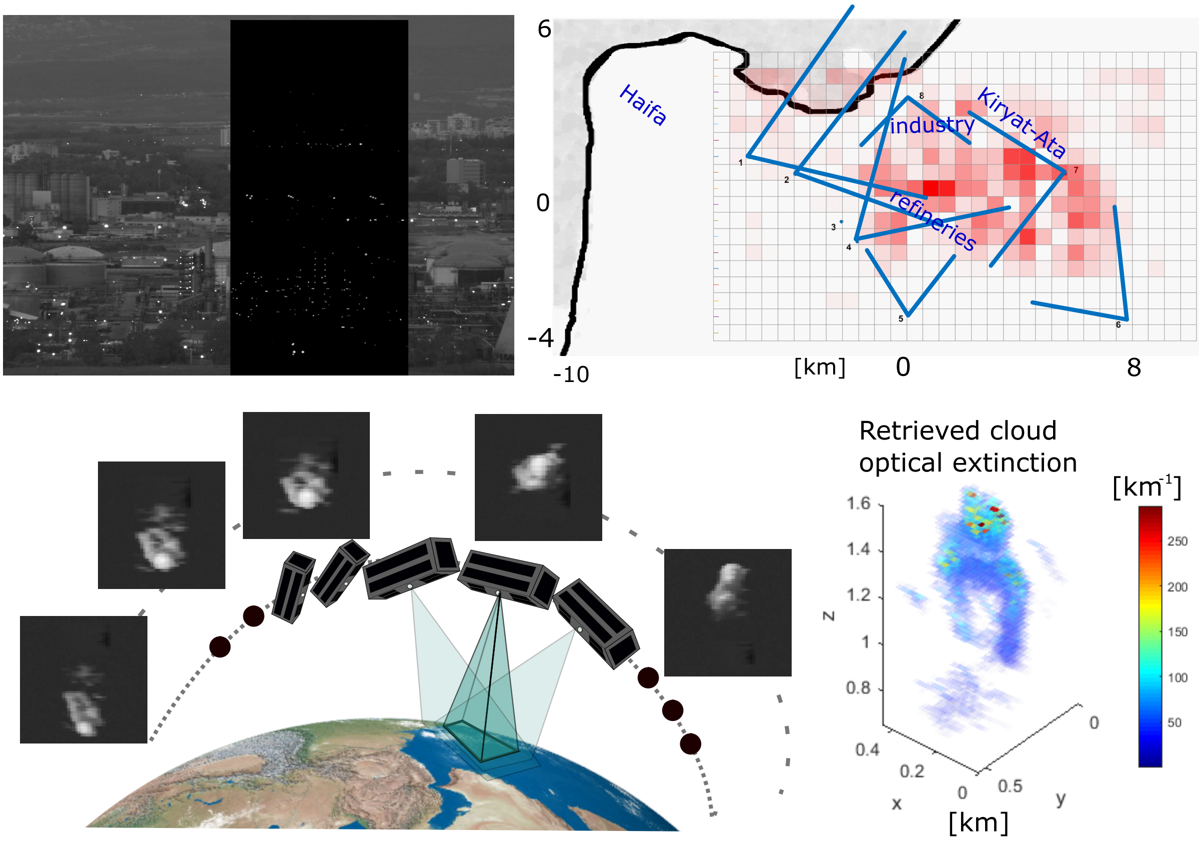

Fig. 1. [Top] Tomography of the turbulence strength in Haifa Bay, based on a set of cameras observing the region from multiple directions. We show a sample twilight image of the scene, overlayed with a night-time image, showing bulbs whose scintillation is measured. [Bottom] The CloudCT setup: spaceborne imagery for scattering-based tomography of clouds.

Following ground experiments and algorithms we derive for this task [3, 4] we now work on demonstrating scattering-based CT of clouds, based on spaceborne imagery. The framework is the CloudCT project, funded by the ERC. Images will be taken by 10 polarization-sensitive cameras [5], each on a nano-satellite (Fig. 1). Polarization is a key for retrieving microphysical properties of the water droplets in the clouds. The satellites will be in low-Earth orbit, with $\approx$ 100km between neighboring satellites. They will be in a coordinated formation, to point simultaneously at each acquired cloud field.

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