Optical Wave Propagation through von Kármán Vortex Streets

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Abstract: A study of optical wave propagation through von Kármán vortex streets is presented. Ray tracing simulations show that these structures can have a considerable impact on optical wave propagation.

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1. Introduction

Understanding optical wave propagation through atmosphere is crucial in a variety of applications such as laser communications, remote sensing or observational astronomy. Atmosphere presents both small scale and large scale variations of refractive index which perturb optical wave propagation. Propagation through small scale inhomogeneities such as optical turbulence is generally modeled by a diffractive approach. In this study, we focused on optical wave propagation through large scale structures. This propagation can be understood by refractive techniques such as ray tracing.

Several models such as the U.S. 1976 model [1] have been devised to characterize the vertical distribution of refractive index. While such models are sufficient for a number of applications, they are often unable to describe refractivity fluctuations in the lower part of the atmosphere, known as the boundary layer, whose behavior is directly influenced by its contact with earth or sea surface. Mesoscale modeling can then be used to simulate spatial and temporal variability of the atmosphere at high resolution [2].

Von Kármán vortex streets (VKVSs) are repeating patterns of counter rotating vortices that can appear downwind of isolated islands that rise above the boundary layer (see satellite image of Madeira island in Fig. 1(a)). Mesoscale modeling of the refractvity fluctuations induced by a VKVS over the island of Madeira is presented in a companion paper [3]. In what follows, the outputs of this mesoscale simulation are used to study optical wave propagation through the VKVS.

2. Ray tracing simulation

The mesoscale simulation provided 4D-fields of dry air pressure P_d, water vapor pressure P_w and temperature T which were used to compute the field of refractive index at wavelength λ: $n(\lambda) = 1 + [A_d(\lambda)P_d + A_w(\lambda)P_w]/T$,where $A_d(\lambda)$ and $A_w(\lambda)$ are given by [1]. The dimensions of the considered refractive index inhomogeneities l_0 were large compared to the Fresnel distance: $l_0 \ll \sqrt{\lambda L}$, where λ is the wavelength and L is the propagation distance. Propagation through these inhomogeneities was thus modeled by using ray-tracing techniques. The evolution of the ray-position vector $\boldsymbol{r}$ is governed by the ray-tracing equation

$$\frac{d}{ds}\left(n\frac{d\boldsymbol{r}}{ds}\right) = \nabla n, \qquad (1)$$

where s is the scalar distance along the ray and ∇n is the refractive index gradient [4]. Equation (1) was solved using Euler's method with a step size of 50 m. The refractive index, its vertical gradient, and its transverse gradient were interpolated on a cross-section plane using cubic-splines. This cross-section plane contained the initial ray and the Earth's center. The ray was traced on the cross-section plane using the vertical gradient. Transverse deviations from this plane were obtained using the transverse gradient. Note that Earth's surface was modeled as an oblate ellipsoid in the calculations.

3. Simulation results

The VKVS was responsible for large anomalies of vertical temperature gradient in the upper region of the boundary layer (between 500 and 1000 m above sea level). These anomalies manifested into the organized distribution of

refractive index gradients shown in Fig. 1(b) and propagated downstream with the VKVS pattern. Fig. 1(b) also illustrates the trajectories of optical rays originating from Madeira and propagating though the VKVS. One can observe the presence of regions were the concentration of rays can be 2 to 3 times stronger than average. These regions coincide with the recurring pattern of the VKVS and follow its temporal evolution. The temporal evolution of the altitude of a ray sent horizontally from Madeira at an altitude of 500 m above sea level after 220 km propagation is represented in Fig. 1(c). The ray altitude can vary by more than 200 m over the course of 90 min. Note that the ray-tracing results of Fig. 1(b) do not show the deviation of the rays in the direction orthogonal to the cross-section plane. These transverse deviations are relatively small since the VKVS creates transverse gradients of refractive index that are about two orders of magnitude smaller than their vertical counterparts. The temporal evolution of this transverse deviation is shown in Fig. 1(c). One can note that the transverse deviations from the cross-section plane are never larger than 5 m after 220 km propagation.
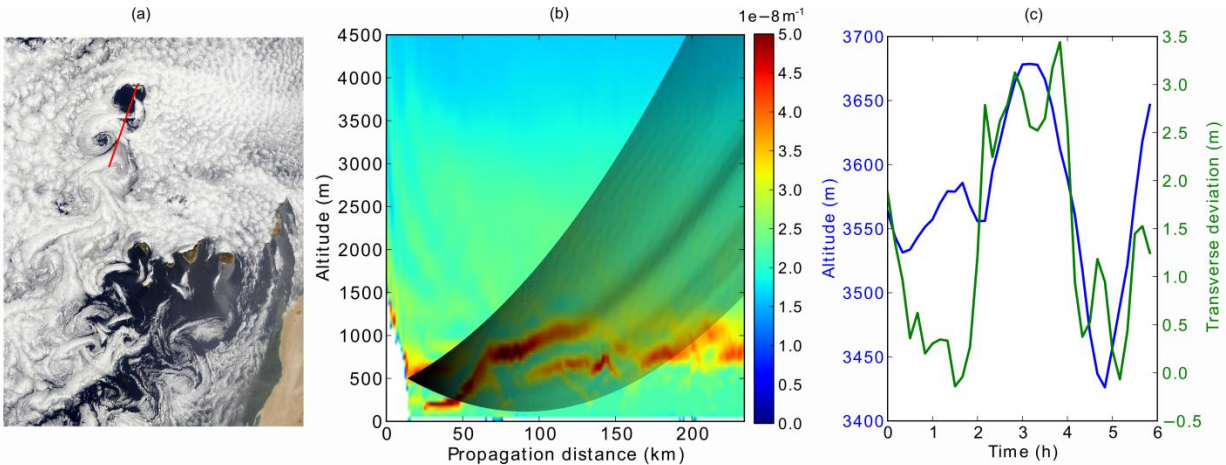

Fig. 1. (a): Satellite image of Von Kármán vortices over Madeira. The red line corresponds to the cross section of Fig. 1(b). (b): Propagation of 1001 rays with an angular spacing of 20 μrad through the VKVS. The rays are either originated from 500 m (left) or 1000 m (right) above sea level. The background image corresponds to the vertical cross section of refractive index vertical gradient. Wavelength is 1550nm.

5. Conclusion and perspectives

Mesoscale modeling of boundary layer refractivity was used to study the effect of von Kármán vortex streets (VKVSs) on optical wave propagation. Ray-tracing simulations showed that these structures can have a considerable impact on optical wave propagation. One can imagine studying the structure of von Kármán vortex streets by on-site observation of these propagation effects. Work is ongoing to study the effect of refractive index fluctuations of smaller spatial scales on wave propagation.

6. References

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