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Atmospheric Optical Turbulence and Inertial Subrange Spectra Over the Ocean

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Abstract: A comprehensive dataset was collected in a recent field campaign to characterize the marine atmospheric boundary layer (MABL). Results of turbulence spectra are presented here to show the complications in estimating C_n^2 in the MABL.

1. Introduction

The lowest ~1 km of the atmosphere over the ocean is referred to as the marine atmospheric boundary layer (MABL) and is characterized by the presence of turbulence. This is the region through which beams from optical sensors and high energy laser (HEL) weapons propagate during maritime engagements. Turbulence in the MABL significantly impacts the performance of these systems through various processes, particularly atmospheric scintillation.

Atmospheric scintillation over land surfaces has been studied extensively over the past 20 years, but over the ocean, advancement in this subject lags mainly due to the lack of adequate datasets caused by the challenges inherent in making precise measurements in the marine environment. Hence, it is crucial to take every opportunity to make measurements suitable for optical turbulence studies within the MABL atmsophere. As part of the Quantifying and Understanding Environmental Turbulence Affecting Lasers (QueTal) - a project sponsored by the US Joint Directed Energy Transition Office (DE-JTO), under its Multidisciplinary University Research Initiative (MRI), we collaborated with the Coupled Air Sea Processes and Electromagnetic ducting Research [1] West Coast field campaign (CASPER-West) during September-October 2017 to make extensive measurements of the MABL. As a result, the CASPER-West dataset became extremely valuable for quantifying optical turbulence properties. A comprehensive summary of the electro-optical (EO) measurements during CASPER-West is given in [2]. Wauer [3] also conducted a comprehensive analysis of the variation of the structure function parameter for the index of refraction, C_n^2, using measurements from the *R/P FLIP* and a research aircraft, a Twin Otter operated by the Naval Postgraduate School.

The focus of this study is optical scintillation. In addition to obtaining C_n^2 from direct high-rate measurements, we also examined the fundamental questions such as the validity of the Kolmogorov theory on the turbulence spectra in the inertial subrange. From both theoretical and experimental results, past studies have indicated conditions of systematic deviations from the -5/3 law over the inertial subrange. The implication of such deviations can be significant to optical turbulence study since the calculation of C_n^2 and the connection to optical propagation is based on the assumption that the inertial subrange spectra follow the -5/3 power law. Here, we present a systematic study on the power spectrum in the inertial subrange using the measurements from *FLIP*. A new method to automatically identify the turbulence inertial subrange will first be described, and the systematic deviation of the spectra slope from the -5/3 value will be presented. Although the results presented here are from the turbulent velocity spectra, we expect that the results for the spectra of temperature would be similar, which is the subject for future research.

2. CASPER-West FLIP Measurements

CASPER-West was conducted from September to October 2017. Details of the measurement area and coordinated sampling platforms can be found in [2]. *FLIP* was moored at ~26 NM south-southeast of Pt. Mugu, California, and the measurements from the air-sea interaction mast (ASIM) installed on the port-side boom (Figure 1a) provided the main dataset for this analysis. Figure 1b shows C_n^2 obtained from the high-rate temperature and humidity measurements from seven levels on *FLIP*, together with the air-sea temperature difference (ASTD) and wind speed over the entire measurement period. ASTD denotes the thermal stability of the measured marine atmospheric surface layer (MASL), while wind speed is indicative of the dynamic forcing within the MASL. The color shadings in Figure 2b highlight C_n^2 variations associated with a few special events identified as Santa Ana winds or cold front passage (see [3] for details).

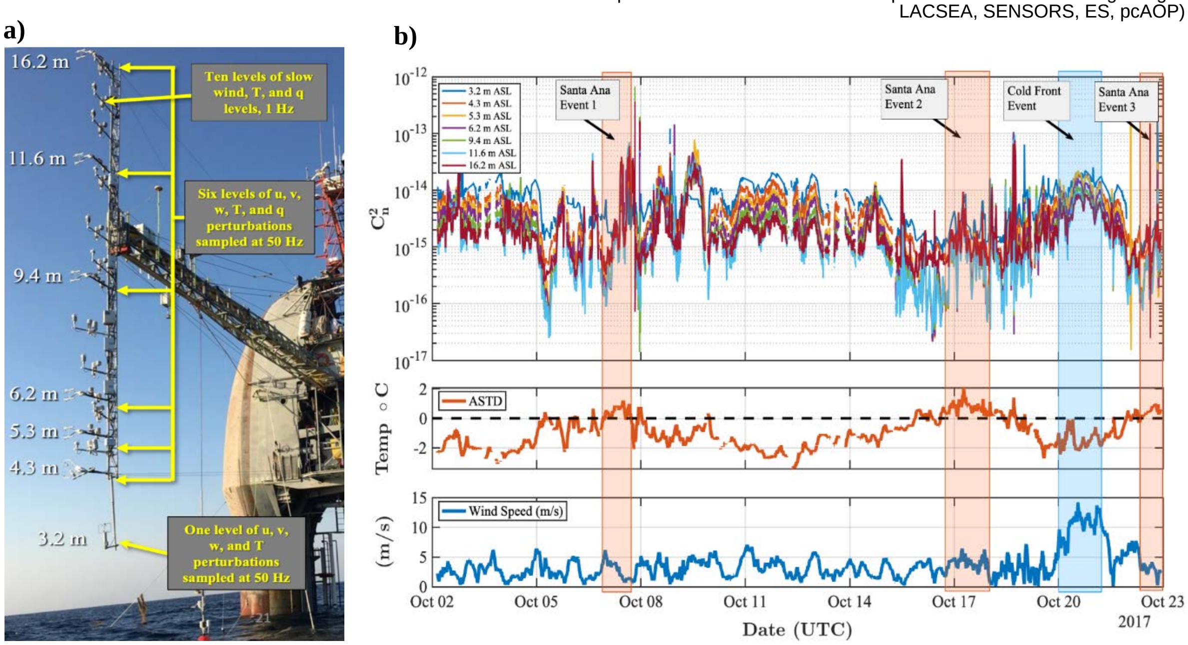

Fig. 1. **a**) Placement of meteorological instruments for mean and perturbation measurements of state variables on the *FLIP* ASIM; **b**) Temporal variations of C_n^2 at all measurement levels (top), air-sea temperature difference (middle), and wind speed (bottom) for the entire period of CASPER-West. All figures are from [3].

3. Identifying the Turbulence Inertial Subrange

The inertial subrange of the turbulence kinetic energy spectrum is usually identified by manually comparing the slope of a given power spectrum in log-log scaling with a -5/3 line. There are three issues with this approach: (1) this method is not conducive to analyzing a large dataset to gain statistically robust results; (2) this approach does not assess whether or not the identified subrange exhibits isotropy; and (3) this approach presumes the -5/3 power. The algorithm for robust identification of the inertial subrange (ARIIS) has been developed to facilitate empirical studies of the turbulence cascade [4]. ARIIS systematically and robustly identifies the most probable subrange bandwidth in a given velocity variance spectrum. The algorithm is a novel approach since it directly uses the expected 3/4 ratio between stream wise and transverse velocity components to locate the onset and extent of the inertial subrange within a single energy density spectrum. Most importantly, ARIIS does not assume a -5/3 power law but instead uses a robust, iterative fitting technique to derive the slope over the identified range. This algorithm was tested using the comprehensive micrometeorological dataset obtained from *FLIP*.

4. Observed Variations of the Inertial Subrange Slope

ARIIS was applied to all *FLIP* measurements to identify the magnitude of the power law by defining the turbulence inertial subrange as the range of spectra that show local isotropy of turbulence [4,5]. We believe this is the first systematic study on the spectral slope and its variation within the MASL. We showed that, although the -5/3 power law is generally valid, there are significant deviations from this power law within the MASL, particularly near the ocean surface. Further investigations of the deviations from the -5/3 slope suggest the role of surface layer thermodynamics and processes of air-sea interaction, where the observed inertial subrange power varied with altitude, wind speed, wave age, and atmospheric stability. These results will guide us on new analyses for the temperature and water vapor spectra in the inertial subrange.

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