Experimentally Characterizing Millimeter Wave Propagation in Random Media Using a Fan Array Wind Tunnel

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***Abstract*—This paper summarizes the advancements in theoretical modeling and measurement results of a novel experimental setup for characterizing millimeter wave propagation in random media using a 36x36 fan array wind tunnel. The increase and shift in the measured power spectrum of the millimeter wave signal demonstrate the effect of temperature gradients and wind speeds in both the inertial subrange and dissipation regions of turbulence. This setup can be used to develop new models for characterizing electromagnetic propagation through random media in a more consistent and repeatable experimental setup.**

I. Introduction

Scintillation is an important phenomenon that has been studied for decades and is defined as the random fluctuations of the amplitude and phase of an electromagnetic (EM) signal due to atmospheric turbulence. Developing a better understanding and accurately modeling the effects of turbulence on propagation is essential for a wide variety of applications. Scintillation can significantly impact the quality of radio frequency (RF) signals used in radar, terrestrial and satellite communication systems, as well as providing an opportunity for remote sensing of atmospheric turbulence. Past experiments studying scintillation over long distances in the outdoors showcase many logistical challenges. In such setups, there is imperfect *a priori* knowledge about naturally generated turbulence, creating inconsistent and uncontrollable conditions. Furthermore, it is also difficult to deploy transceiver hardware that is sensitive to the very weak amplitude and phase effects, as the signal must be phase locked and output power carefully calibrated.

An overview of the benefits and preliminary results of an experimental setup using a 36x36 fan array wind tunnel (FAWT) in the Center for Autonomous Systems and Technologies (CAST) at the California Institute of Technology (Caltech) is described in [1]. The following sections will (i) expand on the theoretical analysis for modeling by including the dissipation region, (ii) provide an overview of the meteorological measurements, and (iii) present measurements results showing the effect of turbulent mixing at different scales.

II. Theoretical Analysis

The channel of a line of sight (LoS) propagation link between a transmitter and receiver can be modeled as a turbulent medium causing scintillation (Fig. 1). For the context of this experiment, the use of a monostatic radar means that the system is a folded version of a LoS path with a single-bounce reflector setup, and is still applicable to this model.

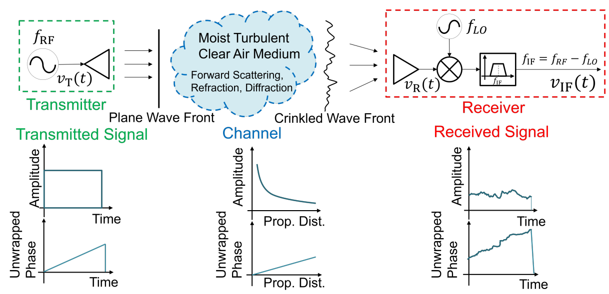

Fig. 1. Effect of atmospheric turbulence on EM wave propagation.

A. Line-of-sight propagation model for RF scintillation

The continuous-wave (CW) intermediate frequency (IF) signal at the receiver can be modeled as:

$$v_{IF}(t) = Ae^{\chi(t)}e^{j(2\pi f_{IF}t + \phi(t) + \varphi(t))} \tag{1}$$

where A is the received signal amplitude, f_{IF} is the IF frequency, $\phi(t)$ is the oscillator phase noise, and $\chi(t)$ and $\varphi(t)$ are the log-amplitude and phase scintillations, respectively.

For homogeneous and isotropic media in the lower troposphere, the power spectral densities (PSD) for log-amplitude and phase scintillations, respectively, are given by [2], [3]:

$$S_\chi(f) = 8\pi^2 Rk^2 \int_{2\pi f/v}^{\infty} \frac{d\kappa\kappa\Phi_n(\kappa)F_\chi(\kappa)}{(\kappa^2 v^2 - (2\pi f)^2)^{\frac{1}{2}}} \tag{2}$$

$$S_\varphi(f) = 8\pi^2 Rk^2 \int_{2\pi f/v}^{\infty} \frac{d\kappa\kappa\Phi_n(\kappa)}{(\kappa^2 v^2 - (2\pi f)^2)^{\frac{1}{2}}} \tag{3}$$

where $k = 2\pi f_{RF}/c$ is the wave number of propagation, f_{RF} is the RF carrier frequency, c is the speed of light in a vacuum, v is the mean wind speed, f is frequency offset from the carrier, $\kappa_0 = 2\pi/L_0$ is the outer scale wave number of turbulence, and L_0 is the outer scale length of turbulence. The function $F_\chi(\kappa)$ is the amplitude-variance spectral weighting function, and for plane waves is:

$$F_\chi(\kappa) = \frac{1}{2}\Big(1 - \frac{\sin(R\kappa^2/k)}{R\kappa^2/k}\Big) \tag{4}$$

$\Phi(\kappa)$ is the refractive index wavenumber spectrum of irregularities, defined as the three-dimensional Fourier transform of the covariance of refractive index fluctuations:

$$\Phi(\kappa) = \frac{0.033C_n^2}{\kappa^{11/3}}\mathcal{F}(\kappa\eta) \tag{5}$$

where κ is the wavenumber, $\mathcal{F}(x)$ is the dissipation function, and η is the Kolmogorov microscale. Analytical expressions for the log-amplitude and phase scintillation PSDs have been derived in the inertial subrange of turbulence. However, inclusion of the dissipation region necessitates the use of numerical methods to calculate the PSDs.

B. Turbulence Scales and Dissipation Region

For experiments done in CAST, the operating regime of the turbulent flow is beyond the inertial subrange. Thus, the larger frequencies and wave numbers in the dissipation region must be considered. The $-5/3$ Kolmogorov spectrum power law for wind speed (WS) fluctuations in the inertial subrange corresponds to a $-8/3$ power law for the log-amplitude and phase scintillation spectrum. However in the dissipation region the dropoff is exponential as the turbulent eddies become too small and dissipate into heat [4]. The model for the WS PSD, accepting the Taylor frozen flow hypothesis, is [5]:

$$S_u(f) = C(v\varepsilon/2\pi)^{2/3} f^{-5/3} f_\eta((2\pi f/v)\eta) \tag{6}$$

where $C = 1.5$ is a proportionality constant, u is the instantaneous WS, and ε is the turbulent dissipation rate. The Komogorov microscale η is calculated as:

$$\eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \tag{7}$$

where ν is the kinematic viscosity of air, which is a known constant for a given temperature. The model for $f_\eta(x)$ is:

$$f_\eta(x) = e^{-\beta x} \tag{8}$$

for a constant $\beta = 5.2$.

For refractive index, which is a passive scalar, one model for the dissipation function of refractive index fluctuations is the Hill bump model [2]:

$$\mathcal{F}(x) = P_4(x)e^{-\alpha x} \tag{9}$$

where $P_4(x)$ is a fourth-order polynomial function based on numerical approximations, and constant $\alpha = 1.1090$. These equations are used to model the scintillations and WS PSDs in order to compare the experimental results with theory.

III. Measurement Results

Measurement results shown here have the heaters placed on the sides of the FAWT pointed towards the center (Fig. 2). This allows the flow dynamics to be determined solely by the FAWT without obstruction while still generating a large temperature gradient. This differs from the results shown in [1] where the heaters were placed directly in front of the FAWT.

A. Meteorological Measurements

The WS PSDs are calculated from the post-calibration constant temperature anemometer (CTA) data, and show the inertial subrange and dissipation region for each fan speed (Fig. 3). The CTA measurements are used to determine ε from spectral fitting, which is used to calculate η and applied to the dissipation function for the refractive index fluctuations.

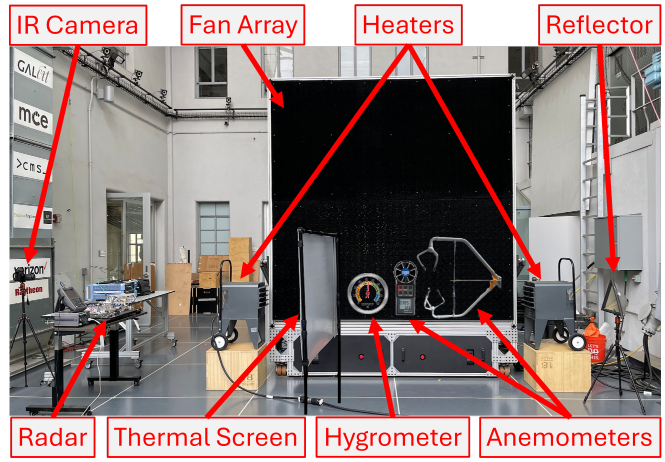

Fig. 2. CAST experimental setup.

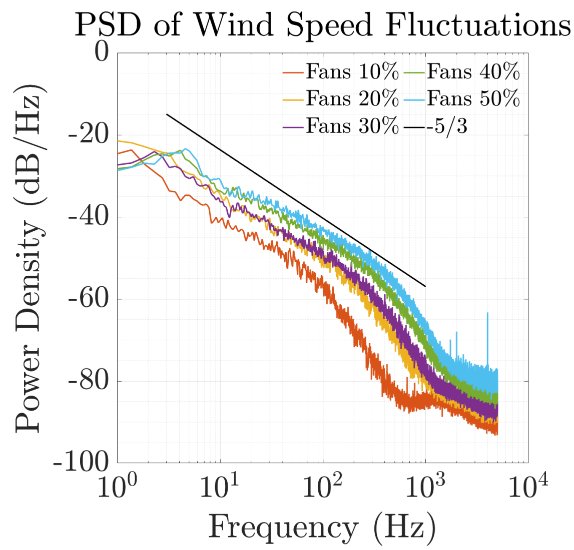

Fig. 3. PSD of WS fluctuations.

Snapshots of the temperature at different locations in the flow are taken for various fan speeds (Fig. 4). From this, the resulting temperature gradient can be calculated at each pixel. The temperature gradient is averaged across the cross sectional area of the collimated beam from the radar antenna. These meteorological values are used to estimate the value of C_n^2 that is used in the model for the amplitude and phase scintillation PSDs. Since the magnitude of the temperature fluctuations is not constant across the entire propagation path, C_n^2 is integrated along the path (Fig. 5), and is assumed to be negligible for the area beyond the FAWT edges since there is no temperature gradient nor significant turbulent mixing.

B. Radar Measurements

The phase noise of the received baseband (BB) signal for different fan speeds is compared with the theoretical scintillation models (Fig. 6), using the measured ε from the CTA and C_n^2 from the temperature gradients. Although there

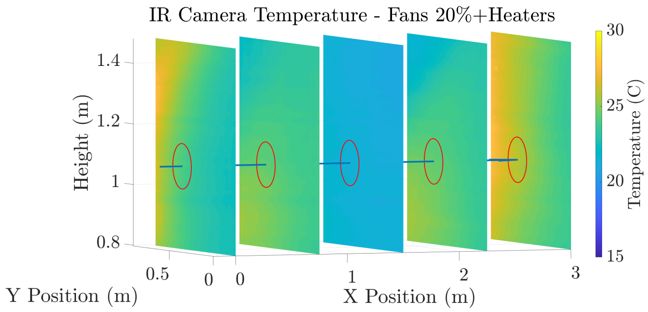

Fig. 4. Temperature profile of flow for Fans 20% with heaters.

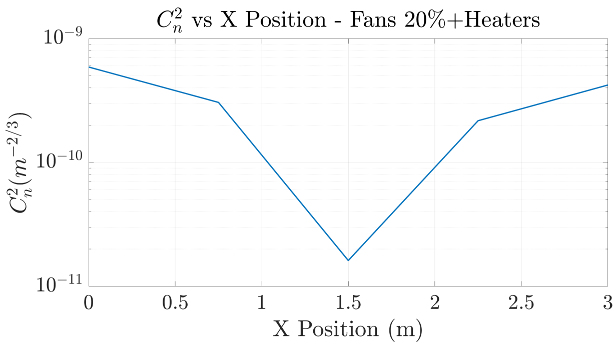

Fig. 5. C_n^2 at different positions in the flow.

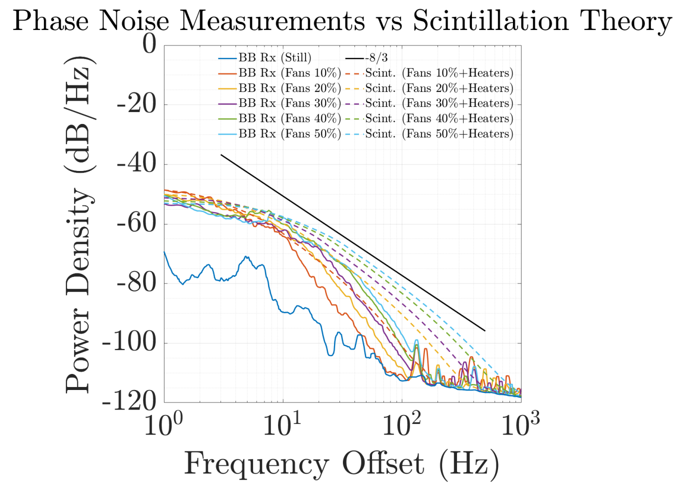

Fig. 6. Measured phase noise vs theoretical scintillation using measured ε.

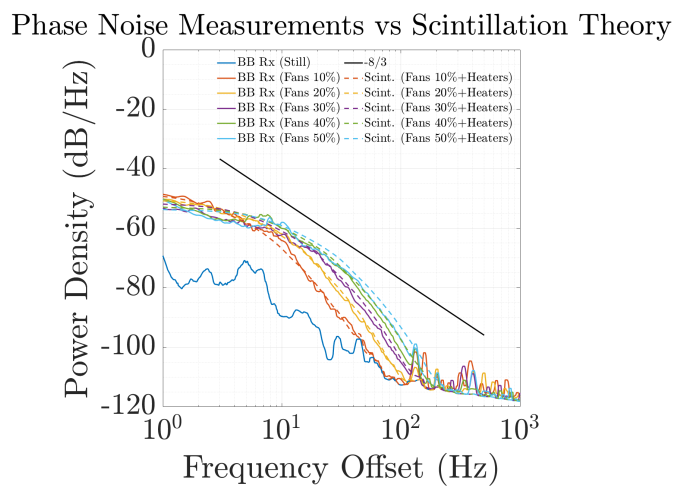

Fig. 7. Measured phase noise versus theoretical scintillation using scaled ε.

are slight discrepancies, the qualitative behavior is accurately described through the shifts in the spectrum and steeper dropoff. By scaling ε, the theoretical scintillation can more closely resemble the measured phase noise (Fig. 7). However, further analysis needs to be done to justify the arbitrary scaling factor and improve the theoretical understanding and accuracy of these models.

IV. Conclusion

The most recent developments in theoretical modeling and measurement results for an experimental setup using a FAWT to study scintillation have been described in this paper. Inclusion of the dissipation region of turbulence allows for more comprehensive and accurate modeling. The radar measurements demonstrate that even with a new heater configuration, qualitatively accurate results can be achieved in this consistent and controllable experimental environment. This shows the flexibility and capabilities of performing scintillation studies using a FAWT for continued advancements in theory and modeling.

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