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Fade Statistics and CNR Improvement of an Equal-Gain Coherent Receiver Array

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1. Introduction

It is well known that the performance of a coherent laser radar (CLR) system can be seriously degraded by the presence of atmospheric turbulence along the propagation path. For example, the effective aperture size of a single element monolithic coherent detector is limited by the atmospheric coherence diameter.[1] The detection and processing of laser communication signals are also drastically affected by turbulence-induced fading of the received signal.[2] The performance of any CLR system can be measured on the basis of *carrier-to-noise ratio* (CNR) and *fractional fade time* analysis including mean duration of fades. Previous theoretical analyses and experimental data have shown that the use of a coherent receiver array system can overcome such deleterious atmospheric effects by appropriately combining the intermediate frequency (IF) signals from a number of independent receivers.[3-5] In this paper we present a summary of recent experimental data obtained at the BMDO Innovative Science and Technology Experimentation Facility (ISTEF) outdoor range that illustrates CNR improvement and probability of fade statistics as a function of the number of apertures associated with an equal-gain (EG) multi-aperture CLR system.

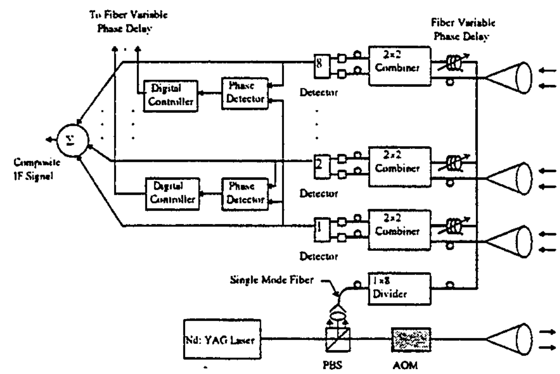

Figure 1 Block diagram of equal gain array receiver.

2. Multi-Aperture Array Receiver

The eight aperture coherent detection system used to acquire the data was built and tested at the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida. A block diagram of the system is shown in Fig. 1. The transmitter is a 60mW diode-pumped Nd:YAG laser operating at 1.06μm. A portion of the transmitted signal is split off by a polarizing beam splitter to serve as the local oscillator (LO) while the other portion is shifted up by 27.12 MHz by an acousto-optic modulator (AOM). The LO is fiber-coupled to a 1×8 optic fiber divider for the receiver. A collection of eight 1-cm-diameter apertures are positioned in a circular ring configuration which encircles the transmitted beam. Each aperture is fiber-coupled to a 2×2 optic fiber combiner which mixes the received signal with the LO to form the IF signal at 27.12 MHz. The signals from the eight apertures, which are typically uncorrelated and out of phase because of atmospheric turbulence effects, are co-phased to a reference signal (that we can choose) by an electro-optic phase-locked loop (EOPLL) to obtain phase coherence between each of the received signals. Phase adjustment of each received signal is accomplished by using a piezoelectric cylinder wrapped with fiber to shift the phase of the received signal. Finally, the co-phased IF signals are summed with equal gain.

3. Experimental Details

The field tests were conducted on February 13, 1998 at BMDO's ISTEF. The target was an aluminium plate (50cm × 50cm) covered with 3M reflectance tape (3M# 7610) which is considered as a large rough target, located at 1 km downrange.

A scintillometer instrument was used to simultaneously measure values of the atmospheric index of refraction structure constant C_n^2 and inner scale l_0 of atmospheric turbulence.

Instrumentation for measuring the amplitude variation in time due to atmospheric turbulence is shown in Fig. 2. The input signal in this figure is the IF signal from the array system given by

$$I_{IF} = A_s A_{LO} \cos\left[(\omega_s - \omega_{LO})t + \varphi\right], \qquad (1)$$

where A_{LO} is the constant amplitude of the LO and φ is the random phase induced by turbulence. At the output of the lowpass (LP) filter the signal is described by

$$I_{LP} = \frac{1}{2} B C A_s A_{LO} \cos(\varphi_{AGC}), \qquad (2)$$

where B and C are constants and φ_{AGC} is the constant phase delay from the AGC circuit. Thus, the LP filter output (2) is directly proportional to the signal amplitude A_s.

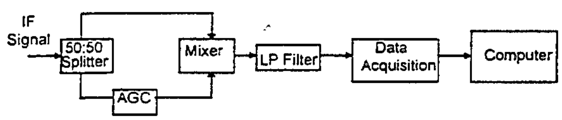

Figure 2 Block diagram of the sampling circuit.

The signal was sampled at a rate of 10 kHz over a one minute period by a data acquisition board and saved in a computer for future analysis. It has been proved that the frequency of the laser intensity fluctuations due to atmospheric turbulence is less than 3 kHz which implies that a 10 kHz sampling frequency is fast enough to get the signal variations.[6] The total number of sampled points is 600,000.

By turning on the EOPPL of the M active apertures of the array system, the IF signal amplitude of the coherent summation from M apertures (C.S.M.) was sampled as $(A_1, A_2, ..., A_{600000})_{C.S.M.}$. By turning off the EOPLL of the M active apertures of the array system, the IF signal amplitude of the incoherent summation from M apertures (I.S.M.) was sampled as $(A_1, A_2, ..., A_{600000})_{I.S.M.}$.

4. Results

Improvement in the responsivity of the multi-aperture system can be determined by the *Mean Coherent Array Gain Factor* (MCAGF). This quantity is defined by the ratio

$$\text{MCAGF} = \frac{\text{Mean Power of C.S.M.}}{\text{Mean Power of I.S.M.}} = 1 + (M-1)\frac{\bar{A}_s^2}{\overline{A_s^2}}, \qquad (3)$$

where M denotes the number of active apertures of the array system and A_s is the random amplitude of the received signal. The numerator is obtained with all channels co-phased whereas the denominator is the same number of channels without co-phasing, the latter of which behaves much like a single large aperture system with the same collected signal. Thus, this factor is the responsivity advantage of a coherent array compared with a monolithic receiver with the same collecting aperture area. Measured values of the mean noise power was the same for the coherent and the incoherent summations of M element receivers. The MCAGF is therefore equal to the ratio of the mean CNR of the coherent summation of M elements compared with the mean CNR of a single large aperture with the same collected signal.

From the sampled data of the field tests, the mean CAGF of the system with M apertures over 1 minute can be calculated by

$$\text{MCAGF} = \frac{\left(\sum_{k=1}^{600,000} A_k^2\right)_{C.S.M.}}{\left(\sum_{k=1}^{600,000} A_k^2\right)_{I.S.M.}}. \qquad (4)$$

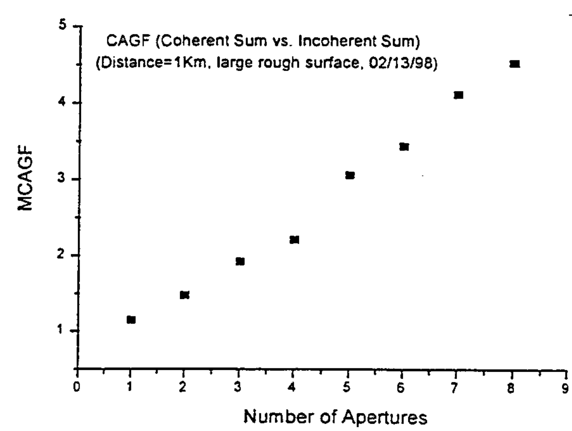

Figure 3 Mean CAGF as a function of number of apertures of the system.

In Fig. 3 we display the MCAGF of Eq. (4) as a function of number of apertures M of the system obtained on February 13, 1998. Measured values of C_n^2 varied from 1.64×10^{-13} to 2.41×10^{-13} m$^{-2/3}$, the inner scale was ~4 mm, and the temperature was ~24°C.

Clearly, the signal improvement of the coherent array increases linearly with the number of apertures compared with an incoherent array receiver system (equal to a single large aperture system with the same collected signal).

The probability of fade or *fractional fade time* describes the percentage of time the intensity of the received signal is below some given threshold value designated by I_T. If intensity fluctuations are governed by the probability density function (PDF) $p(I)$, then the probability of fade is simply the cumulative probability defined by

$$P(I \leq I_T) = \int_0^{I_T} p(I)\,dI. \qquad (5)$$

It is customary to express the fade intensity level I_T below the mean intensity in decibels (dB), which is described by the fade threshold

$$F_T = -10\log_{10}\left(\frac{<I>}{I_T}\right), \qquad (6)$$

where the brackets < > denote a long-time average (assumed equal to an ensemble average).

From the sampled amplitude, the probability of a signal fade and the average duration of fade for the signal power can also be calculated as a function of the number of co-phased channels and of the threshold levels. For the coherent summation of M channels, the power is normalized by the long-time average power (over one minute) of the incoherent summation of the same number of channels. Because there is no co-phasing when we are doing the incoherent summation, the CNR is not changed compared with that from one channel. This normalization allows us to take into account the improvement in the mean CNR and in the second normalized moment of the analyzed signal, which are the two main interests in using a multi-aperture array system with a coherent summation.[3]

The probability of fade and mean fade time calculated from the measured data are shown in Figs. 4 and 5, respectively, as a function of the number of channels coherently summed and of the fade threshold level. From Fig. 4, for example, we see that the probability of fade for $F_T = -5$ dB is decreased by a factor of 1.5×10^5 using the coherent summation of eight apertures as compared with using only one channel. Similarly, in Fig. 5 we see that, for the same threshold value $F_T = -5$ dB, the mean duration of fade is decreased by a factor of 3 using the coherent summation of eight apertures compared with one channel.

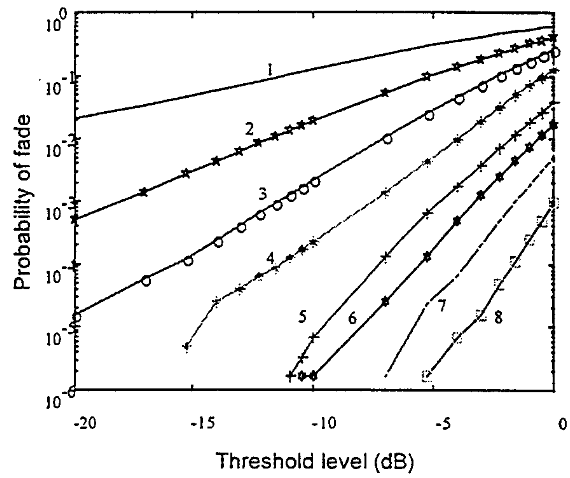

Figure 4 Probability of fade as a function of the threshold level and number of apertures for a rough surface target.

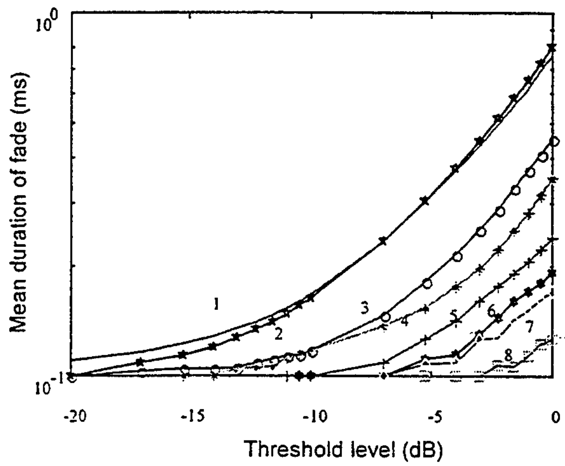

Figure 5 Mean duration of fade plotted as a function of the threshold level and number of apertures for a rough surface target.

5. Summary

In this paper we have presented recent experimental data concerning the performance of a CLR receiver array system as measured by its mean CAGF and probability of fade statistics. Based on the experimental data, it can be concluded that atmospheric turbulence effects can be significantly mitigated by the use of such coherent receiver systems as compared with more conventional single aperture systems.

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