Bootstrap Beacon Creation for Dynamic Wavefront Compensation

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ABSTRACT

The task of delivering sufficient level of airborne laser energy to ground based targets is of high interest. To overcome the degradation in beam quality induced by atmospheric turbulence, it is necessary to measure and compensate for the phase distortions in the wavefront. Since, in general, there will not be a cooperative beacon present, an artificial laser beacon is used for this purpose. In many cases of practical interest, beacons created by scattering light from a surface in the scene are anisoplanatic, and as a result provide poor beam compensation results when conventional adaptive optics systems are used. In this paper we present three approaches for beacon creation in a down-looking scenario. In the first approach we probe whole volume of the atmosphere between transmitter and the target. In this case the beacon is created by scattering an initially focused beam from the surface of the target. The second approach describes generation of an uncompensated Rayleigh beacon at some intermediate distance between the transmitter and the target. This method allows compensation for only part of the atmospheric path, which in some cases provides sufficient performance. Lastly, we present a novel technique of "bootstrap" beacon generation that allows achieving dynamic wavefront compensation. In this approach a series of compensated beacons is created along the optical path, with the goal of providing a physically smaller beacon at the target plane. The performance of these techniques is evaluated by using the average Strehl ratio and the radially averaged intensity of the beam falling on the target plane. Simulation results show that under most turbulence conditions of practical interest the novel "bootstrap" technique provides better power in the bucket in comparison with the other two techniques.

Keywords: artificial laser beacon, turbulence, scintillation, anisoplanitism

1. INTRODUCTION

Interest in developing adaptive optical systems for the laser communications, directed energy weapons, and laser target designators has developed. The key goal of any adaptive optical system is to compensate for the wavefront errors induced by atmospheric turbulence. In the present case, adaptive optical solutions are to be used to compensate for the turbulence effects in order to deliver sufficient level of airborne laser energy to ground based targets. To overcome the degradation in the beam quality induced by the atmospheric turbulence, it is necessary to measure and compensate for the phase distortions in the wavefront. A beacon capable of probing the atmospheric turbulence is required. In astronomy a natural star can sometimes serve as a beacon, and in other cases a high altitude artificial beacon can be created. However, in most non-astronomy cases there is no suitable beacon for wavefront sensing available, and as a result, a beacon must be created artificially. Generally, this must be achieved by passing the laser beam to the target plane along the intended path for the compensated beam. As a result, the light falling on the target which is intended to be a beacon is often corrupted by turbulence effects. In many realistic cases, the artificially generated beacon is anisoplanatic due to the combination of long propagation path and strong turbulence conditions. The combination of these factors can also result in a beacon corrupted by strong scintillation.[3]

In this paper we present three techniques for beacon creation in a down-looking scenario for exploring beam control performance tradeoffs: 1) Scattering from the surface of the target, 2) generating a Rayleigh beacon part way to the target, and 3) applying a novel "bootstrap" technique by placing a series of compensated Rayleigh beacons between the aperture and the target. In the first technique we probe the whole volume of the atmosphere between the transmitter and the target. In this case, the beacon is created by the laser beam, propagated through the turbulence, and scattered from the surface of the target. The second strategy uses a single Rayleigh beacon which is created at some intermediate distance between transmitter and the target. This method allows compensation for part of the atmospheric path, which in some cases provides improved performance. Lastly, we present a novel "bootstrap" beacon generation technique. In this approach a series of compensated beacons is created along the optical path, with the goal of providing a physically smaller beacon at the target plane. The first beacon is an uncompensated Rayleigh beacon generated at some distance between the transmitter and the target. The back-scattered field carries the information about wavefront errors induced by part of the turbulent atmosphere. This information is used by the adaptive optical system to precompensate the next beacon to be generated at some further distance from the aperture. The bootstrapping procedure continues until the beacon reaches the target. In all cases there is no tracking information available, and this information must be obtained from some other aspects of the scene or target. We conjecture that a tracker based on a block-matching algorithm using an image in the scene,[8, 9] may provide sufficiently accurate tracking information.

The beacon created using first approach is generally larger than the isoplanatic angle, and due to the scattering from the surface of the target, will also be corrupted by the coherent laser speckle effect. The second approach will generally provide a beam with smaller angular extent compared to the case of scattering from the surface of the target, though probing only part of the atmosphere. The bootstrap technique probes the whole volume of the atmosphere, and provides a suitably small beacon at a useful distance from the aperture. The number of beacons and their location in the bootstrap approach are the key parameters for effective compensation. We investigate this key issue in this paper.

The reminder of this paper is organized as follows. In the next section we discuss theoretical considerations for beam projection through the turbulence, specifically examining a down-looking scenario. The simulation developed to study the performance of artificially created beacon using strategies described above is presented in Section 3. Results are presented in Section 4, and conclusions are drawn in Section 5.

2. THEORETICAL BACKGROUND

Light passing through the turbulent atmosphere becomes distorted. This distortions are caused by variations in the index of refraction along the optical path of the beam. These variations are caused by turbulence-induced temperature fluctuations in the atmosphere resulting in density changes. In this section we describe the theoretical characteristics of a beacon laser beam arriving at the target plane. The impact of turbulence on an optical beam of a given path through the atmosphere is commonly characterized by the parameters: r_o, θ_0 and σ_χ^2. The Fried parameter r_o is the aperture size beyond which further increases in its diameter result in no further increase in the resolution of an imaging system.[1] The isoplanatic angle θ_0 defines the maximum angle between two optical paths for which the two paths may be regarded as having approximately the same turbulence distortions.[3] The Rytov variance σ_χ^2 is the variance of the log-amplitude fluctuation of the field in the plane of the receiving optical system, and is a measure of whether the effects of the turbulence on a particular system is dominated by phase effects. In this paper we consider a down-looking scenario, in which the aircraft carrying the laser is flying at various altitudes and pointing laser beam at the target located at ground level with a fixed slant path distance of 5000 m. For a collimated, or nearly collimated outgoing beam r_o, θ_0, and σ_χ^2 can be calculated using the following formulas.[3]

$$r_0 = 2.1\left[1.46\sec(\phi)k^2\int_0^L dzC_n^2(z)\right]^{-3/5} \tag{1}$$

$$\theta_0 = \left[2.914k^2\sec(\phi)^{8/3}\int_0^L dzC_n^2(z)z^{5/3}\right]^{-3/5} \tag{2}$$

$$\sigma_\chi^2 = 0.563 k^{7/6} \left[\sec(\phi)\right]^{11/6} \int_0^L dz C_n^2(z) z^{5/6} \tag{3}$$

where the wave number is given by $k = 2\pi/\lambda$, λ is the wavelength, L is the length of the propagation path in the vertical direction, ϕ is the zenith angle, and z is the altitude. The structure constant $C_n^2(z)$ characterizes the strength of the index of refraction fluctuations. The Hufnagel-Valley profile for the $C_n^2(z)$ is given by.[1]

$$C_n^2(z) = 5.94 \times 10^{-53}(\upsilon/27)^2 z^{10} e^{-z/1000} + 2.7 \times 10^{-16} e^{-z/1500} + A e^{-z/100} \tag{4}$$

where A and υ are free parameters.[2] The parameter A sets the strength of the turbulence near the ground level and υ represents the high altitude wind speed. Typical values for the A and υ are $1.7 \times 10^{-14}\mathrm{m}^{-2/3}$ and 21 m/s respectively. Beam spreading and beam wander are the beam counterparts to the image blurring and dancing. Turbulence scales that are large with respect to the beam size cause tilt, while turbulence scales that are small relative to the beam size cause beam broadening. As a result, a long exposure of the beam would result in the superposition of many realizations of the random wander of the broadened beam, which is an important consideration for beam pointing and tracking. However, the short-term broadening is important for pulse propagation and high-energy laser systems which have accurate trackers. The mean square short-term beam radius of an initially collimated beacon laser in the target plane $\langle \rho_s^2 \rangle$ is given by[3]

$$\langle \rho_s^2 \rangle = \frac{4L^2}{(kD)^2} + \left(\frac{D}{2}\right)^2 + \frac{4L^2}{(k\rho_0)^2}\left[1 - 0.62\left(\frac{\rho_0}{D}\right)^{1/3}\right]^{6/5} \tag{5}$$

where the transverse correlation length ρ_0 is related to the Fried parameter r_0 by $r_0 = 2.1\rho_0$. The isoplanatic angle projected to the target plane has radius $L\theta_0/2$, which we shall refer to as the isoplanatic patch radius ρ_I

$$\rho_I = \frac{L\theta_0}{2} \tag{6}$$

We evaluate beam parameters r_0, θ_0, σ_χ^2, ρ_I, and $\langle \rho_s^2 \rangle$ as a function of the altitude z, for wavelength $\lambda = 1.06\mu$m, transmitting lens diameter of $D = 0.5$m, and constant 5000 m optical path. The result of evaluating these parameters for the geometry of interest is shown in Fig.1. The structure constant $C_n^2(z)$ shown in Fig.1(a) for low altitudes takes values close to $10^{-14}\mathrm{m}^{-2/3}$, representing fairly strong turbulence conditions. Fig.1(b) shows that r_0 varies from 16 mm to 10 cm depending on the altitude. Fig.1(c) shows that for our geometry isoplanatic angle is of the order of 2.5μrad if the propagation takes place at low altitudes and reaches 45μrad at about altitude of 3000m. Also, from Fig.1(e), it can be seen that the short term RMS beam radius, representing root mean square instantaneous spot radius in the target plane after passing through the atmosphere, will be significantly bigger than the isoplanatic patch radius, indeed smallest feasible spot size is up to about 100 times ρ_I . This inspection leads us to conclude that beacon anisoplanatism will be a strong effect for beacons created by scattering light from the target. Fig.1(d) demonstrates that significant fluctuations of the field amplitude are expected, especially at low altitudes. As a result, we conclude that scintillation will be non-negligible over many paths of practical length for beam projection systems, and that simulations are an appropriate means of modelling atmospheric optic effects and the performance of strategies for mitigating turbulence effects.

It is evident that there are certain difficulties and limitations for artificial laser beacon generation for wavefront sensing and beam control. In the case when the beacon is created by scattering an initially focused beam from the surface of the target, the footprint of the beacon laser in the scene is considerably larger than the isoplanatic patch. As a result, light scattered from a surface in the scene will propagate through many atmospheric paths on its way back to the aperture which, while correlated, are not identical to each other. The turbulence induced abberations from all these paths arrive superimposed at the aperture and hence make computing a useful set of deformable mirror commands based on a wave front sensor measurements of this field exceedingly difficult. An alternative method is to generate of an uncompensated Rayleigh beacon at some intermediate distance between the transmitter and the target, by scattering light from atomic,molecular, and aerosol content in the atmosphere. This method allows compensation for only part of the atmospheric path, that is, the part between the beacon and the transmitter. It was shown in [4] that generation of Rayleigh beacon can be effective, and under some conditions provide results close to those obtained in the case of an ideal point source beacon in the target plane. For the down-looking geometry examined here the approach of using a single Rayleigh beacon may be not as effective due to the fact that the strongest turbulence is located near the ground. A novel "bootstrap" technique for artificial beacon creation, which allows dynamic wavefront compensation, involves formation of a series of compensated beacons at increasing distances from the aperture. The bootstrap strategy probes the whole volume of the atmosphere using multiple step precompensation of the beacons, that should help achieve a smaller footprint of light distribution in the target plane, reduce effects of scintillation, and reduce the effects of beacon anisoplanatism present in other approaches for beacon creation. In the next section we describe a simulation used to compare the performance of the compensation techniques discussed above.

3. SIMULATION APPROACH

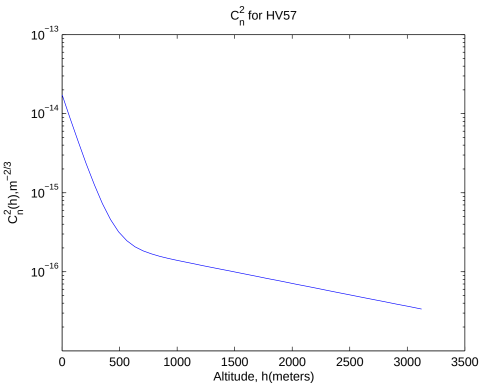
In this section we describe the simulation developed to study the performance of the strategies for creating artificial beacons explained in the previous section. The main body of the simulation used in all three approaches is a three way propagator and can be summarized by the following steps :

1. an artificial laser beacon is propagated through the atmosphere from the the laser aperture to the beacon plane.
2. light is scattered from the surface of the beacon plane, which is modelled as an incoherent source.
3. scattered light propagated back through the atmosphere and intercepted by the aperture is used to form wave front sensor measurements, using a least square reconstruction paradigm, used to compute deformable mirror commands.
4. a compensated outgoing beam is reflected from the surface of corrected deformable mirror model and propagated through the atmosphere back to the target plane, where performance metrics are computed.

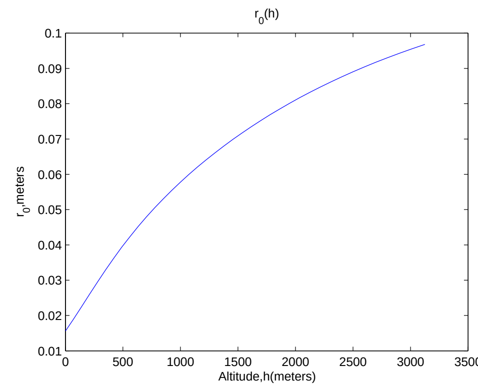
In order to account for the effects induced by the turbulent atmosphere on the propagated field, we represent turbulent volume of the atmosphere using a multiple phase screen model, and a wave front propagator. The phase screens have the statistical correlation properties associated with Kolmogorov turbulence.[10] The mathematical relation of the incident field $U_i(x_p, z_n)$ and the field after the screen $U_t(x_p, z_n)$ can be described by

$$U_t(x_p, z_n) = U_i(x_p, z_n) T_s(x_p, z_n) \tag{7}$$

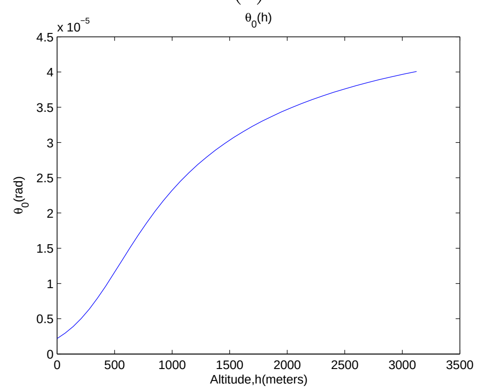
where $T_s(x_p, z_n) = \exp[j\phi_A(x_p, z_n)]$ is a screen transparency function describing random field perturbation. To propagate the field from screen to screen we use the discrete angular spectrum propagator.[5] Unphysical wrap-around error, which arises from light scattered at wide angles, was illuminated using the technique developed by Martin and Flatte.[6] The random phase screens were generated according to technique developed by Cochran[7] and implemented in the MATLAB toolbox called AOTOOLS.[10] The parameter r_0 is required by the phase screen generator, and needs to be calculated for each turbulent layer as a function of the altitude. In this simulation the atmospheric path was modelled with 5 equally spaced, different strength phase screens, with the first phase screen placed in the aperture plane and the last one on some distance away from the target. The laser beacon is propagated from the laser aperture through all the phase screens between the aperture and the beacon plane. The beacon light is then scattered from the surface of the target, for the target plane compensation case, or from the atmosphere in the case of the Rayleigh beacon and "bootstrap" approaches. Scattering from the target plane and the atmosphere was modeled by repeatedly multiplying the phase of the incident field on the surface by a random phase uniformly distributed on $(-\pi, \pi)$, propagating this scattered field back to the aperture, and accumulating the resulting intensities in the wave front sensor detector plane. This approach models the incoherent nature of the scattered field.[11] The number of random scattering phases used here was $N_{sp} = 40$. The focal length was



(a)



(b)



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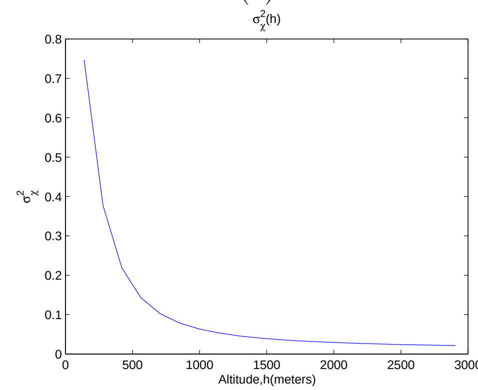
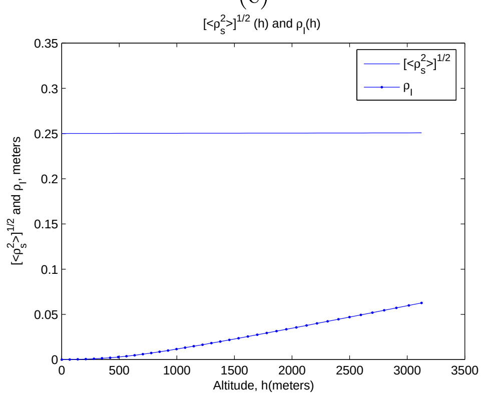


(d)



(e)

Figure 1. Structure constant C_n^2 and beam parameters as a function of altitude, h: (a) Structure constant C_n^2; (b) Fried parameter r_0; (c) Isoplanatic angle θ_0; (d) Rytov variance σ_χ^2; (e) Isoplanatic patch radius ρ_I and Mean square instantaneous spot radius in the target plane $\langle \rho_s^2 \rangle$

chosen to match the propagation path length between the output lens and the required position of the beacon, so that in the absence of the turbulence, a diffraction-limited spot would appear if a collimated beam were passed through the lens toward the required location of the beacon. In the case of delivering the compensated beacon to the target location the focal length of the lens was set to the total distance between the transmitting laser and the target. In bootstrap case, we use the lens with variable focal length in order to deliver the precompensated beacon to the current required position. A wave-optics model of the Hartman sensor was used[5] with subaperture sides in the pupil of length 3.75cm, yielding a total of 70 subapertures in the pupil. The subaperture size was chosen to satisfy the smallest r_0 anticipated for seeing condition of $C_n^2 \leq 10^{-14}\mathrm{m}^{-2/3}$, path length on the order of $L = 5000\mathrm{m}$. The deformable mirror was modeled using a Cartesian array of actuators with bilinear spline influence functions separated by 3.75cm, yielding a total of 89 active actuators inside the pupil. Wave front reconstruction for the outgoing laser beam was computed using the least squares reconstruction technique.[1] An ideal point source was placed in the target plane to provide tilt commands based on the centroid tracker for all of the compensation strategies. We note that cooperative beacon is not expected in practice, and tilt commands will have to be obtained from the scene.[9] The all three approaches were executed for 50 independent realizations of the atmosphere, resulting intensity patterns were accumulated and averaged to obtain the final results which are presented in the next section.
In all three approaches we assumed that the sum of the round trip propagation time and the time required to compute deformable mirror commands was shorter than the time required for the turbulence to change significantly. That assumption allowed us to use the same phase screens for the outgoing beacon illumination laser, the returning scattered light, and the outgoing compensated laser beam.

4. RESULTS AND DISCUSSION

In order to test compensation performance of the simulated AO system we first evaluated it under different turbulence strength conditions. We considered all three techniques for artificial laser beacon creation: scattering from the surface of the target, generating Rayleigh beacon, using backscatter properties of the atmospheric aerosols and the dynamic “bootstrap” beacon creation technique. Considering the fact that the strength of the turbulence is a function of altitude, we studied performance by placing the transmitting laser at different altitudes: 3000, 1500 and 800 meters above the ground level. We kept the slant range a constant 5000 meters for all these cases. In this series of tests the single Rayleigh beacon was generated at the distance of 3000 m from the laser. The performance of these techniques was evaluated by using the average Strehl ratio and compared to the free space and uncompensated beacons. Target plane intensities for various beam compensation scenarios for mild, moderate and strong turbulence conditions are represented in Figs.2, 3 and 4 respectively. Fig.2(a) represents the case of mild turbulence with transmitting laser located at the altitude 3000 meters, and shows radially normalized target plane intensities of free space created beacon, “bootstrap” created beacon, target plane generated beacon, Rayleigh beacon, and uncompensated beacon with Strehl ratios $1, 0.88, 0.7, 0.58$ and 0.3 respectively. For better visual interpretation images of all target plane average intensities are shown in subplots Fig.2(b,c,d,e,f). Figs.3 and 4 represent the cases of moderate and strong turbulence conditions with the transmitting laser placed at the altitudes 1500 and 800 meters respectively. Corresponding Strehl ratios for moderate and strong turbulence conditions are: $[\ 1, 0.78, 0.52, 0.4$ and $0.23\ ]$ and $[\ 1, 0.55, 0.25, 0.21$ and $0.05\ ]$. Layout of subplots in Figs.3 and 4 is similar to that in Fig.2. Inspection of Figs.2, 3 and 4 shows that “bootstrap” technique provides higher Strehl ratio than either the case of Rayleigh beacon creation or the case of a beacon created by scattering an uncompensated beam from the surface of the target plane. We note that in strong turbulence conditions advantage of “bootstrap” technique is even more pronounced. Though the single Rayleigh beacon has smaller angular extend, it does not probe whole atmospheric path, especially at low altitudes, where the turbulence is strongest. This explains its lower performance compared to the case of beacon creation by scattering from the surface of the target. It was found that the performance of the results depends on the number of the beacons and five beacons was found to be an optimal number to achieve good compensation performance.

In order to investigate the importance of the beacons distribution along the propagation path we test our AO system with different beacons position. We use three different cases for beacon location:1) [1.8 km, 2.8 km, 3.8 km, 4.8 km, 5 km]; 2) [3.1 km, 3.8 km, 4.1 km, 4.7 km, 5 km] and 3) [3.9 km, 4.2 km, 4.5 km, 4.8 km, 5 km]. Numbers in the square brackets give the distance of the beacons in kilometers from the transmitting laser. Results of our simulation showed that all three distribution of the beacon location along the path gave approximately the same final results. For example, for the transmitting laser located at the altitude of 1500m and a slant range of 5000m from the target- first, second and third distributions gave the following Strehl ratios: $0.6374, 0.6200$ and 0.6579. Some additional work is required to fully investigate the optimal number and distribution of beacons used in the bootstrap technique.

5. CONCLUSION

We have explored three techniques for artificial laser beacon creation in look down, shoot down scenario for various turbulence conditions. Performance of three techniques: scattering from the surface of the target, generating Rayleigh beacon at some defined distance, and dynamic “bootstrap” beacon creation technique for wave front sensing and deformable mirror control were compared with each other and also with an ideal case of beacon creation in the absence of the turbulence. Under different turbulence conditions it was found that novel “bootstrap” technique provides higher Strehl ratio compare to the other compensation techniques presented here but more work is required to understand the performance tradeoffs. For example, presented here novel “bootstrap” technique involves generation of multiple Rayleigh beacons along the propagation path and the power requirements for making a single Rayleigh beacon have not been investigated. Additionally, we have only examined least squares phase reconstruction approach, but it is likely that wave control improvements would result from use of more advanced, branch point reconstructor. Finally, we conjecture that it might be possible to use presented “bootstrap” technique in conjunction with the approach based on the contrast optimization.

6. ACKNOWLEDGEMENT

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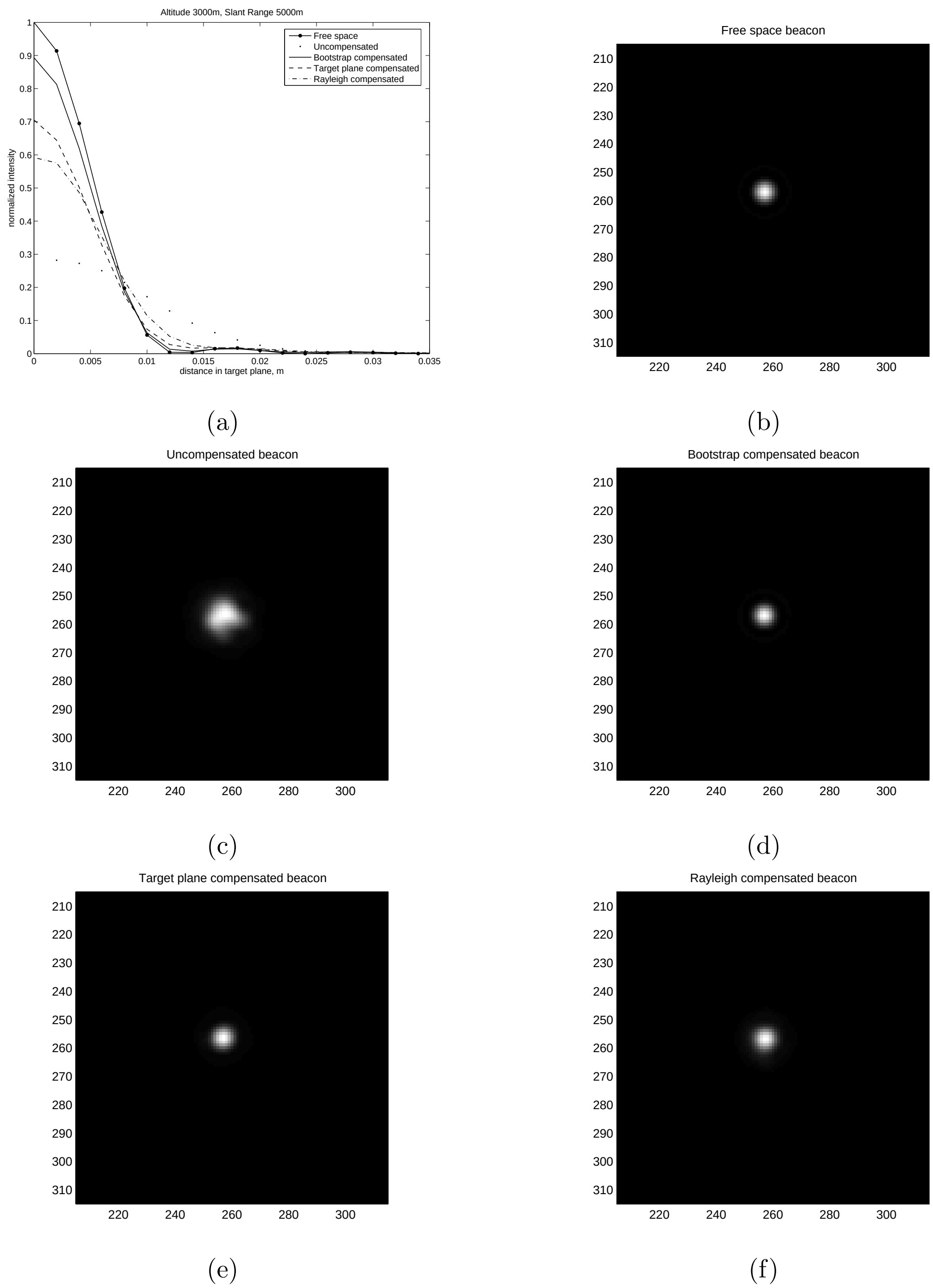

Figure 2. Target plane intensity for various beam compensation scenarios, for 3000m altitude of the transmitter and 5000m of a slant range: (a) Normalized target plane intensity ; (b) Free space beacon at the target plane; (c) Uncompensated beacon at the target plane ; (d) "Bootstrap" compensated beacon at the target plane; (e) Target plane compensated beacon; (f) Rayleigh compensated beacon

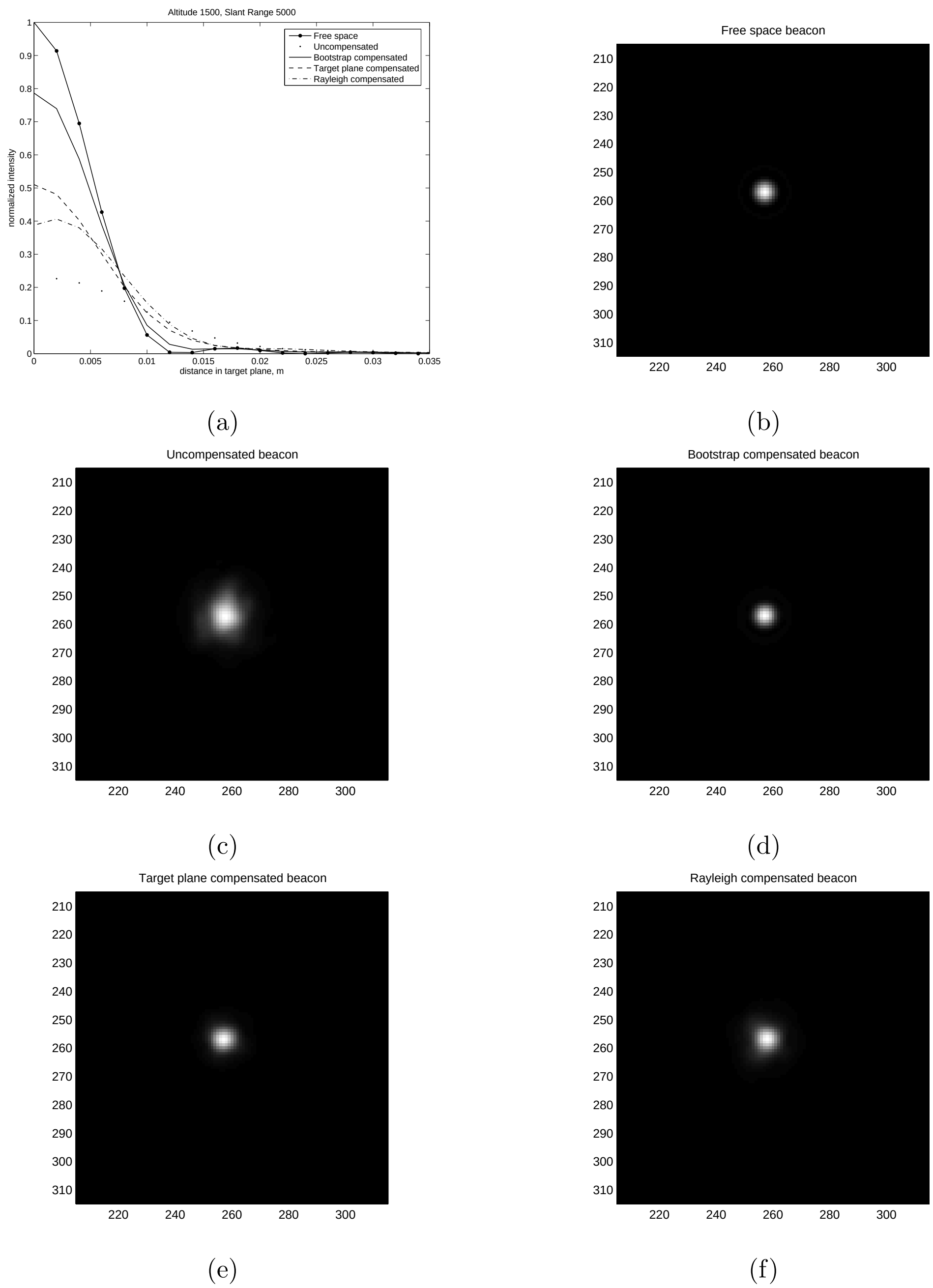

Figure 3. Target plane intensity for various beam compensation scenarios, for 1500m altitude of the transmitter and 5000m of a slant range: (a) Normalized target plane intensity ; (b) Free space beacon at the target plane; (c) Uncompensated beacon at the target plane ; (d) "Bootstrap" compensated beacon at the target plane; (e) Target plane compensated beacon; (f) Rayleigh compensated beacon

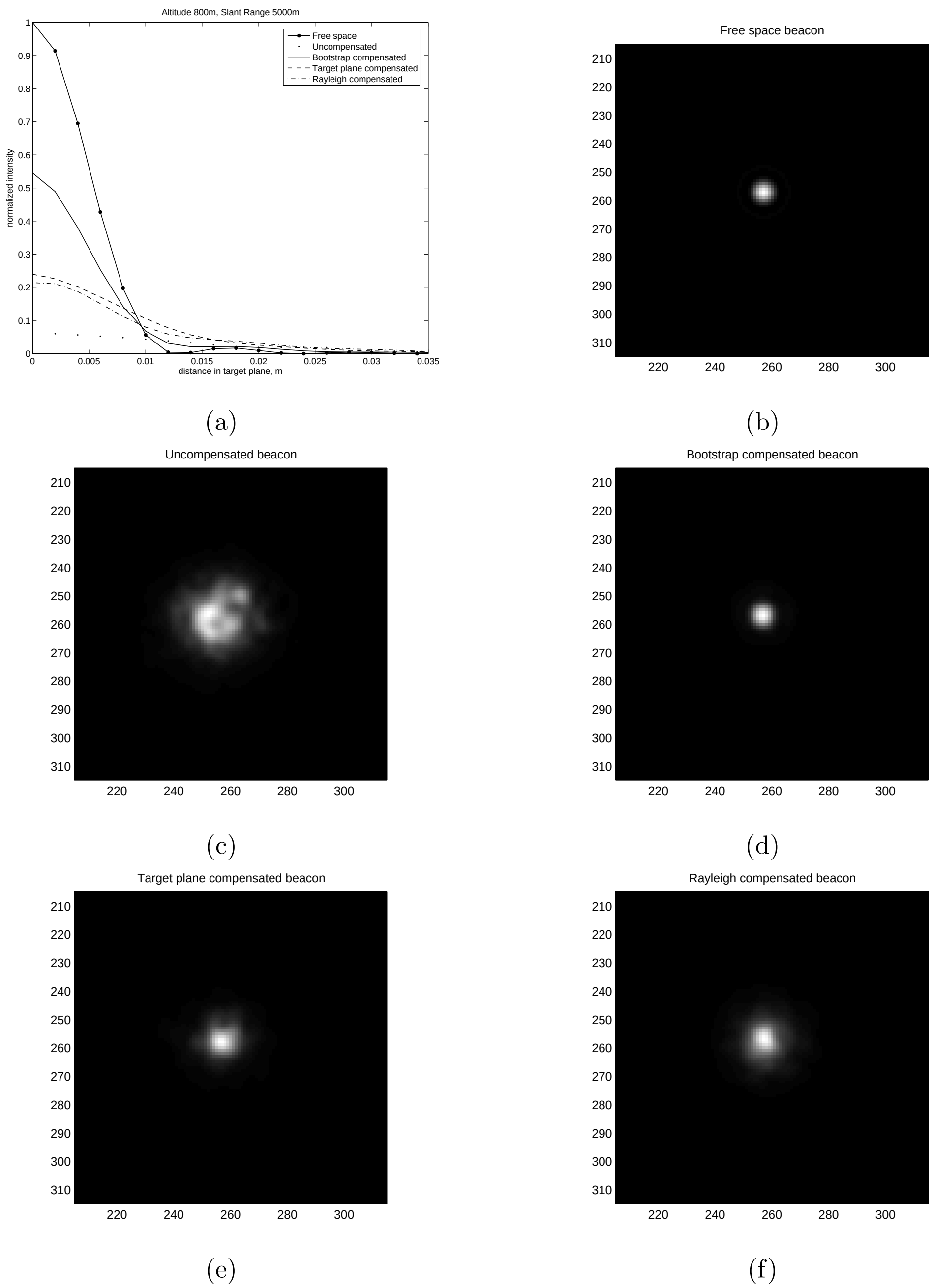

Figure 4. Target plane intensity for various beam compensation scenarios, for 800m altitude of the transmitter and 5000m of a slant range: (a) Normalized target plane intensity ; (b) Free space beacon at the target plane; (c) Uncompensated beacon at the target plane ; (d) "Bootstrap" compensated beacon at the target plane; (e) Target plane compensated beacon; (f) Rayleigh compensated beacon