Antenna Efficiency Optimization in Coherent Lidar Systems

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Abstract: Maintaining very high antenna efficiency is crucial in achieving a high level of performance from coherent lidar systems. This is especially important for space-based operation where available spacecraft prime power limits the transmitter power that can be utilized. We review the impact of wavefront aberrations and misalignment, including lag angle misalignment, on the performance of coherent lidar systems and describe requirements for achieving high antenna efficiency. In space-based large aperture coherent lidar systems, spacecraft rotations result in unacceptable lag angle misalignment loss. A lag-angle compensation system is described allowing for maintenance of high efficiency in large-aperture coherent lidar systems.

Keywords: Coherent Lidar, Wind Measurement

1. Introduction

Global measurements of altitude-resolved vector winds from an Earth-orbiting platform are of interest for both Earth science and weather forecasting applications. The potential for global wind measurements using lidar systems has been recognized for many years [1-3], and the technology has now advanced such that the first global wind measurement mission using direct detection Doppler lidar technology is scheduled to launch in late 2018 [4]. In recent years coherent lidar systems have primarily been considered for space-based wind measurements only in regions of the atmosphere where the aerosol backscatter is relatively high, e.g., the boundary layer and elevated aerosol layers higher in the troposphere. In a companion paper [5], we describe the potential for a coherent detection wind lidar that has sufficient backscatter sensitivity to allow for high percentage coverage throughout the troposphere and lower stratosphere. To achieve high performance the coherent lidar signal detection efficiency must be maintained at a very high level. Below we summarize coherent lidar signal detection efficiency loss mechanisms and describe requirements and techniques to ensure the efficiency is maintained at a high level.

2. Signal Detection Efficiency for Coherent Lidar

As described in the literature [2, 5] the total coherent detection signal is proportional to the total lidar efficiency. We represent the total lidar efficiency as $\eta_T = \eta_{eo}\eta_a = \eta_{to}\eta_{ro}\eta_q\eta_{sn}\eta_a$. In this equation η_{eo} is defined as the lidar electrooptic efficiency, which contains all the transmit and receive optical path losses, η_{to} and η_{ro}, the detector quantum efficiency, η_q, and the coherent detection shot noise efficiency, η_{sn}. The antenna efficiency is the product of the transmit beam truncation efficiency and the heterodyne efficiency. The heterodyne efficiency contains losses resulting from wavefront mismatch between the received signal and local oscillator fields. Reduction of antenna efficiency occurs due to non-optimal sizing of the transmit and local oscillator beams, misalignments, wavefront aberrations in the lasers or optics, and atmospheric refractive turbulence.

The antenna efficiency, which can most conveniently be computed from the overlap integral of the target plane normalized irradiance of the transmit and BPLO fields [2], is given by

$$\eta_a(z) = \eta_{Tt}\eta_{Tb}\frac{\lambda^2 z^2}{A_r}\iint I_{nt}(x,y,z)\, I_{nb}(x,y,z)dxdy\,, \tag{1}$$

where η_{Tt} and η_{Tb} are the truncation efficiencies of the transmit and BPLO beams, respectively.

3. Electro-optic Efficiency

The electrooptic efficiency in well-designed coherent lidar systems can exceed 70%. An example configuration having >66.5% electrooptic efficiency is shown in Figure 1. We emphasize that the electro-optic efficiency does not include antenna efficiency. For example, for designs using single mode optical fibers to collect the signal light (like shown in the Figure), the loss due to mismatch of the received signal field with the fiber single mode field is part of the antenna efficiency. The 99% efficiency shown in the figure is only due to imperfect AR coatings on the fiber input face.

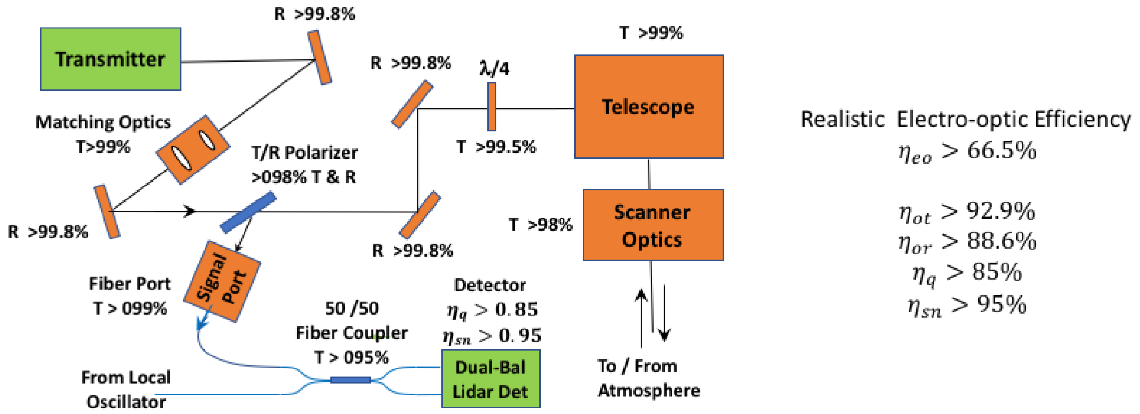


Figure 1. Simplified coherent lidar layout showing electro-optic efficiency greater than 66.5%.

4. Antenna Efficiency

The antenna efficiency is generally defined in Equation 1. Building on our previous analytic antenna efficiency approximation work [6], we have generalized the analytic equations allowing for unmatched transmit and back-propagated local oscillator (BPLO) beam sizes, focus conditions, truncation ratios, and beam qualities (aberrations). The transmit and BPLO beams are assumed centered in the transmit aperture. Our latest improved analytic approximation of the antenna efficiency [7] is

$$\eta_a(z) \approx 2\eta_{clt}\eta_{Tt}\eta_{clb}\eta_{Tb}\rho_{Tb}^2\psi(z) \cdot exp\left[-2\psi(z)\left(\frac{\delta\theta}{\theta_{db}}\right)^2\right] , \tag{2}$$

where
$$\eta_{cli} \approx 1 - 0.162 \exp\left(-\frac{0.25}{\rho_{Ti}} - \frac{0.164}{\rho_{Ti}^2} - \frac{0.873}{\rho_{Ti}^3}\right) , \tag{3}$$

is the central lobe energy of the far field diffraction pattern for either the transmit or BPLO beam, $\theta_{db} = \lambda/\pi\omega_{ob}$ is the diffraction limited divergence of the untruncated BPLO beam, $\delta\theta$ is the misalignment angle between the BPLO and transmit beams, and

$$\eta_{Ti} = 1 - exp\left(-\frac{2}{\rho_{Ti}^2}\right) \tag{4}$$

is the truncation efficiency, with $\rho_{Ti} = \omega_{oi}/a$ being the aperture truncation ratio of the transmit or BPLO beam, ω_{oi} the e^{-2} intensity radius of the beam at the aperture location (prior to truncation), and a the radius of the circular truncating aperture (usually the same as the primary mirror diameter).

The effective Gaussian beam antenna efficiency parameter is given by

$$\psi(z) = \frac{\omega_{db}^2(z)}{\omega_{et}^2(z)+\omega_{eb}^2(z)} = \left(\frac{\omega_{eb}^2(z)}{\omega_{db}^2(z)} + \frac{\omega_{et}^2(z)}{\omega_{db}^2(z)}\right)^{-1} = \left(\frac{\omega_{eb}^2(z)}{\omega_{db}^2(z)} + \frac{\rho_{Tb}^2}{\rho_{Tt}^2}\frac{\omega_{et}^2(z)}{\omega_{dt}^2(z)}\right)^{-1} , \tag{5}$$

Again, we note that these equations assume that both beams are centered in the aperture, and therefore at that location they are centered with respect to each other.

Although we have developed the analytic equations for the effective Gaussian beam sizes, $\omega_{ei}^2(z)$, at arbitrary range (e.g., for the near, intermediate, and far field), due to space limitations we only describe the far field expressions here, which are sufficient for space based lidar performance consideration. In the far field, the effective beam size in Equation 5 is given by

$$\omega_{ei,F} = M_i^2\frac{\lambda z}{\pi\omega_{oi}}, \text{ with } M_i^2 \approx M_{iL}^2 M_{iO}^2 M_{iT}^2 . \tag{6}$$

In this expression, M_{iL}^2, is the beam spreading (or beam quality) factor of the lasers themselves, M_{iO}^2, is the beam spreading due to aberrations in the transmit or BPLO optics, and $M_{iT}^2 \approx \sqrt{\eta_{cli}\eta_{Ti}/f_{c2i}S_{i,F,T}}$ is the beam spreading factor due to the truncation by the aperture. In words, for small to moderate aberration levels, the total far field beam spreading factor is well approximated as the product of individual beam spreading factors as long as the various contributors are statistically independent. The far field Strehl ratio associated with the telescope truncation is $S_{i,F,T} = \left[1 - \exp\left(-1/\rho_{Ti}^2\right)\right]^2$, and f_{c2}, is a correction factor (see Figure 2) needed to match the analytic equations to numerical calculations. This correction factor is related to the correction factor from earlier work [6] by $f_{c2} = f_c/\eta_{cl}$.

Approximations for the optical path related aberration losses were described in the earlier paper [6], and similar more detailed expressions should be used the get higher accuracy, but an even simpler approximate analytic expression has now been developed, which is a good approximation for weak to moderate aberration levels in most efficient coherent lidar designs which have $0.75 < \rho_{Ti} < 1.2$. The simpler expression is $M_{iO}^2 \approx e^{0.5(\gamma\pi\sigma_{iO})^2}$, with σ_{iO} being the rms wavefront aberration in waves, and with the coefficient γ varying between 1.8 and 2.8 depending on the type of aberration that dominates. The aberration type resulting in the highest antenna efficiency reduction (worst case) is the spherical aberration, which is well approximated using $\gamma = 2.8$ for any truncation ratio value, even those outside the 0.75 to 1.2 range.

Using the above equations, the far field antenna efficiency parameter becomes

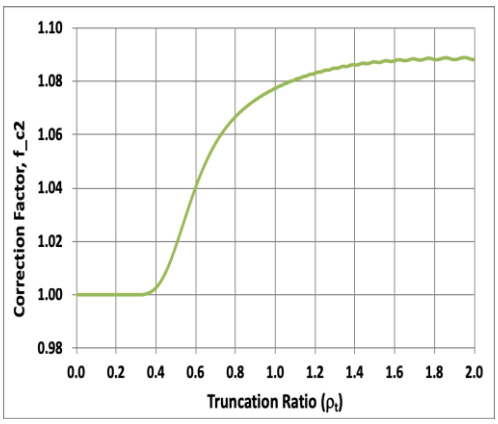
$$\psi_F \approx \left[{M_{bL}^2}^2 {M_{bO}^2}^2 {M_{bT}^2}^2 + \left(\frac{\rho_{Tb}}{\rho_{Tt}}\right)^2 {M_{tL}^2}^2 {M_{tO}^2}^2 {M_{tT}^2}^2\right]^{-1}. \qquad (7)$$

If the transmit and BPLO beam sizes are matched at the aperture, the far field antenna efficiency is

$$\eta_{a,F} \approx 2\eta_{amax,F}\left[{M_{bL}^2}^2 {M_{bO}^2}^2 + {M_{tL}^2}^2 {M_{tO}^2}^2\right]^{-1} exp\left[-2\left[{M_T^2}^2\left({M_{bL}^2}^2 {M_{bO}^2}^2 + {M_{tL}^2}^2 {M_{tO}^2}^2\right)\right]^{-1}\left(\frac{\delta\theta}{\theta_{db}}\right)^2\right], \qquad (8)$$

where $\eta_{amax,F}$ is the far field antenna efficiency for the lidar design in the absence of laser or optical wavefront aberrations (e.g., 0.4 for the Wang lidar design [2]).

The impact of overall wavefront aberrations on the antenna efficiency for a coherent lidar with matched transmit and BPLO beam sizes at the aperture and with truncation ratio of 0.8 (Wang design) is shown in Figure 3. In the figure, the curves represent: solid - numerically calculated using primary aberrations, light dots – numerically calculated using random aberrations, and dashed - aberration analytic model [6] prediction. For the curves and simulation points plotted in the figure, the rms aberrations are assumed to be the same for both the BPLO and transmit beams. If the aberrations are dominated by the telescope, this would be the case, but if the aberrations were dominated by the lasers themselves or by other optics in the system the impact of aberrations would differ from that shown in the figure.



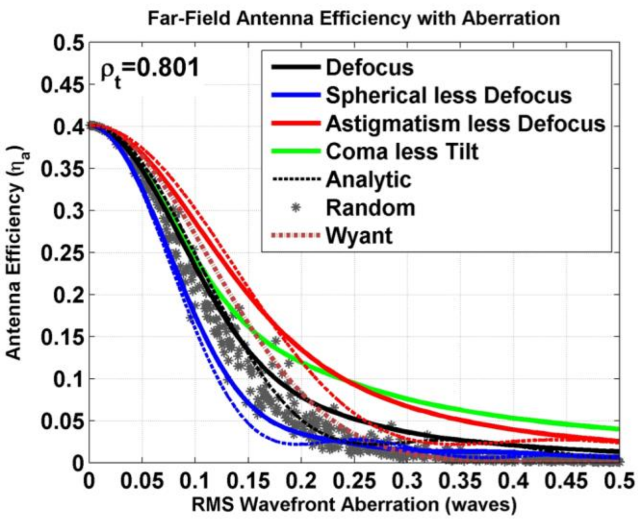


Figure 2. Correction factor f_{c2} used in analytic antenna efficiency equations.

Figure 3. Antenna efficiency reduction due to wavefront aberrations for Wang design lidar.

Figure 3 illustrates the importance of having near diffraction limited optics in the coherent lidar system. For example, if the aberrations are dominated by spherical aberrations the rms wavefront variation must be held to about $\lambda/20$ in order to maintain >80% of peak (unaberrated) performance. This is easier accomplished at longer wavelengths – e.g., $\lambda/20$ for 2 μm is equivalent to ~$\lambda/6.3$ at 633 nm.

Equation 9 is convenient to estimate the far field antenna efficiency of coherent lidar systems with non-perfect lasers and optics. For example, for a Wang design lidar with: no misalignment, transmit and BPLO beam qualities of $M_{tL}^2 = 1.1$ and $M_{bL}^2 = 1.03$, and transmit and BPLO optics rms aberrations dominated by spherical with $\sigma_{tO} = 0.05$ ($M_{tO}^2 = M_{tO}^2 \approx 1.1$) we find $\eta_{a,F} \approx 0.73 \cdot \eta_{amax,F} = 0.29$. So, the efficiency of this example coherent lidar is only about 73% of a perfect lidar of the same design.

Maintaining antenna efficiency loss due to aberrations at levels within 80% of the peak unaberrated performance is possible at longer wavelengths but aberrations must be carefully minimized.

5. Misalignment and Lag Angle Losses

For coherent lidar systems the only signal content that is mode matched the local oscillator (LO) field will be coherently detected. Misalignment of the received field with respect to the LO results in signal loss. Combining Equations 2 and 8 the alignment related efficiency is

$$\eta_{a,\theta}(z) \approx exp\left[-2\psi(z)\left(\frac{\delta\theta}{\theta_{db}}\right)^2\right] \approx exp\left[-2\left[{M_T^2}^2\left({M_{bL}^2}^2{M_{bO}^2}^2 + {M_{tL}^2}^2{M_{tO}^2}^2\right)\right]^{-1}\left(\frac{\delta\theta}{\theta_{db}}\right)^2\right], \quad (9)$$

The antenna efficiency for the Wang and Rye unmatched coherent lidar designs [2] assuming no aberrations vs. misalignment angle between the transmit and BPLO is shown in Figure 4. Note the Rye design has higher overall efficiency and is less sensitive to misalignment, so should it be considered for space-based and other lidar designs, but the Wang design is easily manufactured and can use single mode fiber to collect the signal light and mix it with the LO, so it is frequently utilized. For the Wang design to maintain an alignment efficiency above 95% requires that $\delta\theta < 0.27\theta_{db}$. For example, for a space-based lidar having a 1.5 meter diameter aperture, and no beam aberrations this alignment requirement is $\delta\theta_{lb} < 0.29\ \mu rad$ in the large beam space, which in the small beam space prior to the telescope expansion, where alignment is actually maintained, is $\delta\theta_{sb} < 0.29 \cdot M\ \mu rad$, where M is the magnification of the telescope. For example, if the net magnification, from where the transmit and BPLO beams are aligned to the final expanded output, is $M = 200$, possibly with a two-stage expansion, then $\delta\theta_{sb} < 58\ \mu rad$, which sounds less ominous.

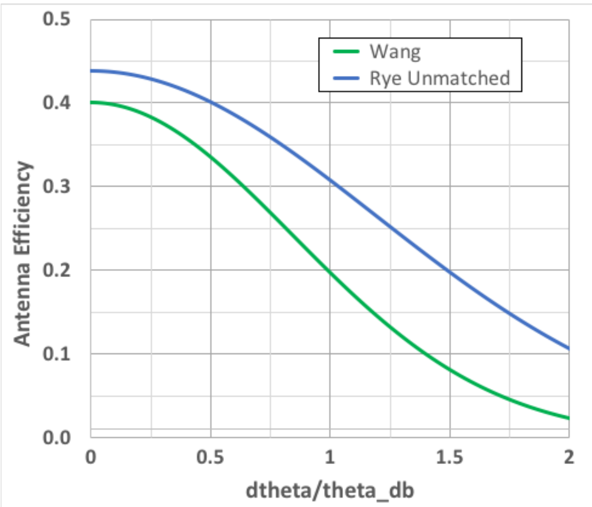


Figure 4. Reduction in antenna efficiency with misalignment for Wang and Rye Unmatched designs.

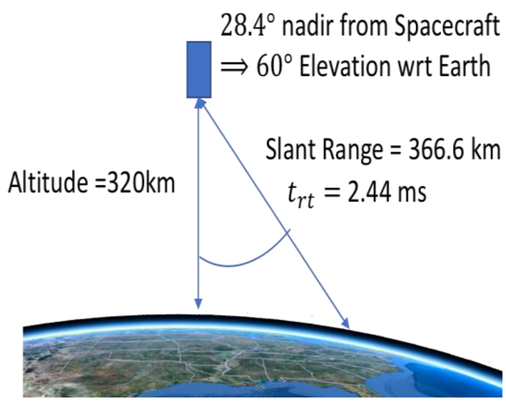


Figure 5. Example measurement geometry for a space-based lidar.

If the lidar platform is rotating, or if a rotating scanner is used to direct the beam, the induced lag angle between the signal return and the LO is given by $\theta_L = \Omega t_{rt}$, where Ω is the rotation rate and $t_{rt} = 2R/c$ is the round-trip time to the measurement volume, with R the range and c the speed of light. An example space-based measurement geometry is illustrated in Figure 5. At the orbit altitude of 320 km the spacecraft circles the Earth every 90.78 minutes, so the spacecraft rotates at a rate of rotates at $\Omega_{orb} = 1.15\ mrad/s$. Given the measurement geometry shown in the figure, the resulting lag and from the orbital rotation alone is $\theta_L = 2.8\ \mu rad$. If uncorrected this lag angle would result in a 20.5 dB loss in antenna efficiency. Clearly this loss is unacceptable and must be removed. For this large 1.5 m diameter aperture example, rotation rates $> 119\ \mu rad/s$ must be sensed and compensated in order maintain the antenna efficiency to within 95% of its peak value.

6. Auto-alignment and Lag Angle Compensation

We are developing a lidar auto-alignment and lag and compensation capability based on using a precision angle measurement sensor to sense instantaneous platform rotation rates $< 100\ \mu rad/s$ and feed this forward to an alignment system in the lidar shown in concept in Figure 6. A laser that is back propagated from the signal fiber is sensed and compared to the transmitted beam. With the rotation rate knowledge, the angle can be offset by the proper amount to allow the lag angle loss to be removed. In addition, any misalignments within the lidar can also be removed automatically. This will be described in more detail in the presentation.

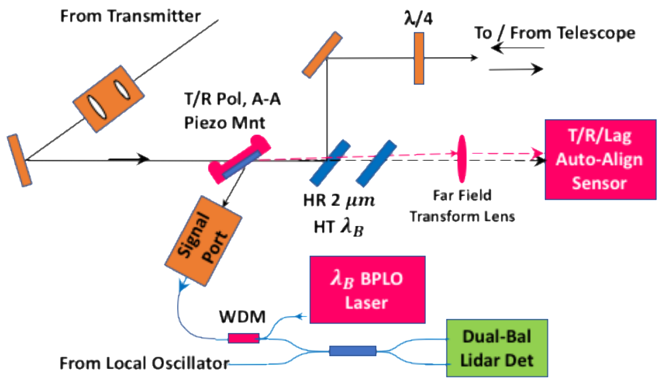


Figure 6. Auto-alignment and lag angle compensation concept.

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