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ADAPTIVE OPTICS IN COHERENT LIDAR WIND MEASUREMENTS: A FEASIBILITY STUDY

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Laser Doppler radar, or Lidar, is widely used for remote sensing of wind velocities. Usable wavelengths for the laser are limited by the effects of atmospheric turbulence. An adaptive optical system is proposed to compensate for turbulence effects on signal power. The feasibility of an adaptive system is considered in light of the effects of speckle from the aerosol target.

Lidar wind measurements are made by sending a laser beam into the atmosphere, and measuring the Doppler shift in the frequency of the radiation reflected by small particles, or aerosols, which are moving with the wind. The frequency shift is proportional to the wind velocity along the beam. (see Drain (2)). Pulsed lidar systems, transmit short pulses and use the time-of-flight of the pulse to determine the range of the reflecting aerosols (see Bilbro (1)). At shorter wavelengths, greater range resolution is achieved, however turbulence effects are increased. Atmospheric turbulence reduces the signal power from a heterodyning receiver in two ways. First the beam width at the target is increased, which increases speckle. Second, the wavefront at the receiver is distorted, resulting in destructive interference of different areas of the beam crossection. The effects of turbulence on lidar signal to noise ratios are described in Frehlich and Kavaya (3).

Adaptive optical systems have been used to compensate for the effect of turbulence on telescope imaging, laser radars, beamed energy and other applications (see Pearson et al (7)). The principal components are a wavefront sensor to measure phase distortion, and a deformable or segmented mirror to impose a phase correction on the transmitted beam or received signal. The wavefront measurements determine the commands to the actuators controlling the mirror shape, making the system adaptive.

Most adaptive optical systems require a point source, such as a star or a glint on a solid target to obtain a useful signal. In the lidar problem, the target is a distributed aerosol, which introduces speckle effects. Zirkind and Shapiro (8), and Kokorowski et al (5) studied speckle in adaptive systems with hard targets, but assumed long decorrelation times. Murty (6) studied speckle effects from distributed aerosols, and found the decorrelation times to be about 1 - 3 μs.

The proposed adaptive optical system and lidar are shown in Figure 1 below. The primary mirror of a Cassegrainian beam expander is made up of identical hexagonal segments with spherical curvature. Each segment is attached to a common rigid base by three piezoelectric actuators to allow a piston motion of the segment, and a two axis tilt. The mirror materials are chosen for high stiffness and resistance to deformation due to heating. A figure sensor measures the position and orientation of each segment for accuracy. The primary mirror is 20 cm in diameter. The combined optical path for both the transmitted and reflected beam helps increases signal power and reduces the effects of turbulence. An hexagonal array of Hartmann sensors is used to measure local slopes of the wavefront. The wavefront is reconstructed from these measurements. Hexagonal arrays are 13 % more efficient than rectangular ones for 2-D signal reconstruction. Due to the weak reflected signal, the wavefront sensor must use coherent detection, and will also be used to sense the

Doppler shift. This requires the design of a new type of sensor. The primary laser transmits bursts of 10 pulses of 100ns duration spaced about 2 μs apart at a wavelength of 2 microns. The bursts are spaced about 1 - 2 ms apart. The local oscillator laser operates at a frequency separated from the primary laser by 100 MHz to obtain wind direction as well as speed. A target range of 1 km is assumed.

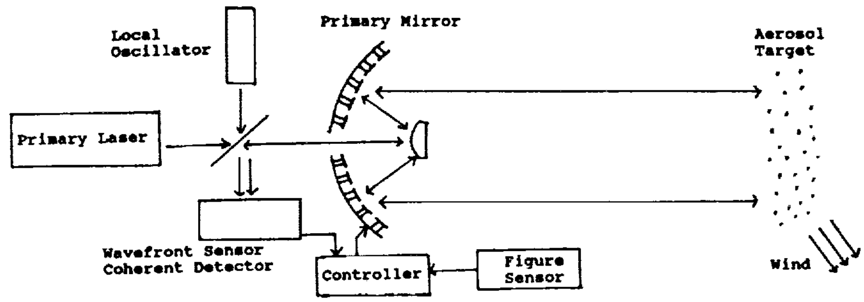

Figure 1.

The spatial and temporal bandwidth are the critical design issues of the system. The spatial bandwidth is determined by the numbers of mirror segments and wavefront sensor cells. The mirror segment size must be comparable to the Airy disk and the Fried coherence length. The mirror segment size is limited by the size of the actuators. A primary mirror with 60 hexagonal segments, 1.28 cm on each side is proposed. A 61 element Hartmann sensor array to measure the wavefront is proposed.

The response times of the mirror segments are .1 - 1 ms, which gives the adaptive system a maximum bandwidth of 1 kHz, which is too slow to compensate for target speckle. Thus the wavefront measurements from one burst of pulses must be used to determine the mirror shape for the next burst of pulses, when the speckle will no longer be correlated. The effect of speckle on wavefront measurement is reduced by averaging over the pulses in a single burst, leaving only the turbulence effects. Greenwood (4) found that systems with bandwidths of 100 to 200 Hz were able to compensate for turbulence effects, and this can be achieved if the laser can produce the necessary pulse repetition rate.

Since the system cannot compensate for speckle, the objective will be to maximize the signal power averaged over the target speckle. Let $E_T(\rho,z)$, $E_R(\rho,z)$, and $E_{LO}(\rho,z)$ be the complex phasors of the transmitted beam, the reflected beam, and the local oscillator beam, assuming a sinusoidal time dependence. Note that each of these beams has a different frequency, but this is not relevant to signal power effects. The signal power is given by

$$|i_s|^2 = K_D \left| \int_A E_R(\rho,0)\overline{E_{LO}(\rho,0)}\,d\rho \right|^2$$

where K_D is a constant describing the detector gain. Signal power is maximized when $E_R\overline{E_{LO}}$ has constant complex phase over the receiver aperture A. It is assumed that E_{LO} has a constant phase across the receiver, so power is maximized by holding the phase of E_R constant over the receiver. The reflected signal is

$$E_R(\rho,0)=\sigma\sum_{j=1}^{N} e^{i\theta_j}E_T(r_j)\,G(r_j;\rho,0)\,e^{i\gamma(\rho)}$$

where r_j is the position of the j'th aerosol, θ_j is a random phase, σ is a reflectivity constant, and G is the Greens function describing propagation in the turbulent atmosphere. If the number of aerosols in the scattering volume is large, the Central Limit Theorem applies, and the reflected signal is a circulo-complex Gaussian random field. $\gamma(\rho)$ is the phase shift induced by the segmented mirror. The transmitted beam $E_T(\rho,z)$ also depends on $\gamma(\rho)$.

If the local oscillator and the transmitted beam are the same in the receiver plane, that is $E_T(\rho,0) = E_{LO}(\rho,0)$, then the speckle averaged signal power can be calculated in the target volume as

$$E[|i_s|^2]=\sigma^2K_r\int_{z_1}^{z_2}\int_{R^2}|E_T(\rho,z)|^4\,d\rho\,dz$$

where K_r is a constant describing the reflectivity and density of the aerosol. From this expression, the signal power is maximized when the mirror shape γ is chosen to reduce spreading of the transmitted beam.

The average signal power can be calculated in the receiver plane as

$$E[|i_s|^2]=K_D\int_A\int_A J(\rho,\rho')\,E_{LO}(\rho,0)\,\overline{E_{LO}(\rho',0)}\,d\rho\,d\rho'$$

where J is the speckle averaged coherence function of the reflected beam

$$J(\rho,\rho')=E[E_R(\rho,0)\,\overline{E_R(\rho',0)}]$$

in the receiver plane, and is given by

$$J(\rho,\rho')=\sigma^2K_r\int_{z_1}^{z_2}\int_{R^2}|E_T(\rho^*,z)|^2G(\rho^*,z;\rho,0)\,\overline{G(\rho^*,z;\rho',0)}\,e^{i(\gamma(\rho)-\gamma(\rho'))}\,dz\,d\rho^*$$

Assuming the local oscillator phase is constant, the signal power is maximized by choosing $\gamma(\rho)$ to give J a constant phase.

Averaging wavefront measurements from several pulses gives a direct measurement of $\measuredangle J(\rho,\rho')$. Let $\theta(\rho) = \measuredangle E_R(\rho,0)$. The k'th cell of the Hartmann sensor measures the average wavefront slope across the cell

$$S_k=\frac{1}{|A_k|}\int_{A_k}\nabla\theta(\rho)\,d\rho$$

By averaging the slope measurements from several pulses, a good estimate of the expected slope can be obtained. The expected slope is

$$E[S_k] = \frac{1}{|A_k|}\int_{A_k} \nabla\Delta J(\rho,\rho)\,d\rho$$

where the gradient is taken with respect to only the first argument of J. For points sufficiently close together, ΔJ can be approximated by

$$\Delta J(\rho,\rho') = \overline{S_k}\cdot(\rho-\rho')$$

where $\overline{S_k}$ is the averaged value of the slope. It remains to reconstruct the remaining values of ΔJ. If ΔJ has the form

$$\Delta J(\rho,\rho') = \phi(\rho) - \phi(\rho')$$

then ΔJ can be recovered from $\overline{S_k}$, k = 1...60 by standard wavefront reconstruction techniques. The tilt and displacement of the mirror segments $\gamma(\rho)$ are then chosen to make $\Delta J(\rho,\rho') = 0$.

In conclusion, adaptive optics is a promising technique for improving the performance of a 2μ lidar wind measurement system. The chief technical challenges are a laser that will give the required output and pulse repetition rate, a combined Hartmann sensor and heterodyne detector, and a suitable wavefront reconstruction algorithm. Further research is required to assess the performance improvement given by the adaptive system under various atmospheric conditions, and an analysis of the convergence and stability of the adaptive system.

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