Turbulence
Lasers, high-energy
thermal blooming

Invited Paper

A COMPLETE PREDICTIVE THEORY FOR THE CORRECTABILITY OF THERMAL BLOOMING IN THE PRESENCE OF TURBULENCE

Beams

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A COMPLETE PREDICTIVE THEORY FOR THE CORRECTABILITY OF THERMAL BLOOMING IN THE PRESENCE OF TURBULENCE

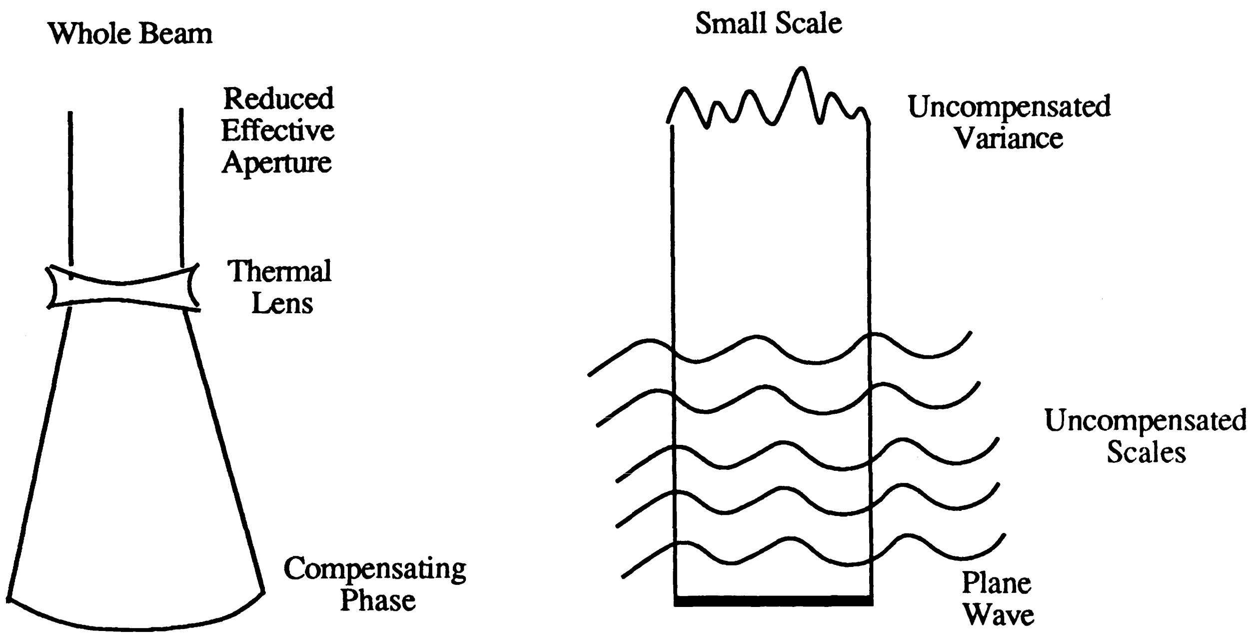
Objective:

A predictive theory for the correctability of thermal blooming in the presence of turbulence that is appropriate to very high Fresnel number beams and that does not rely solely on nonlinear wave optics code calculations.

Approach:

Exploit the facts that the physics of such beams are both local and linear. Calculate an MCF analytically using linear theory and compare with fully nonlinear numerical result. Infer whole beam Strehl from either.

POSSIBLE LIMITATIONS TO THE CORRECTABILITY OF THERMAL BLOOMING



<u>LIMITATIONS</u>
Whole beam instability
Reduction in effective aperture

<u>LIMITATIONS</u>
Phase compensation instability
Uncompensated variance
of phase and amplitude

THREE FRESNEL NUMBERS MEASURE RELATIVE EFFECTS

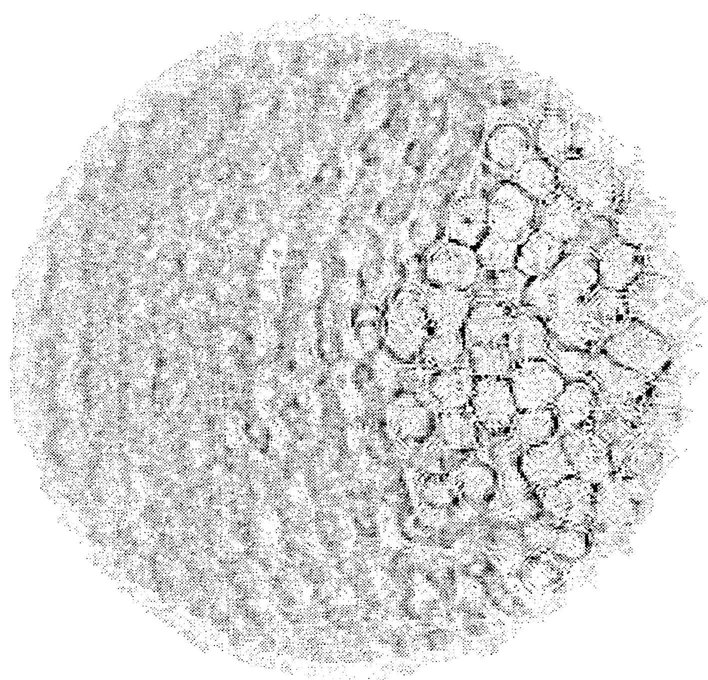
- Three Fresnel numbers of particular significance to thermal blooming phenomena are:
  - Whole Beam Fresnel Number, $N_F = D^2/\lambda L$
  - Turbulence Fresnel Number, $N_T = r_0^2/\lambda L$
  - Actuator Fresnel Number, $N_d = d^2/\lambda L$
- N_F measures relative importance of edge diffraction, conversion of phase to intensity on the scale of the whole beam,
- N_T scales strength of δI produced on a plane wave propagating through atmospheric turbulence.
- N_d measures the tendency for phase-only adaptive optics to produce (unwanted) small scale δI.

THE WHOLE BEAM FRESNEL NUMBER IS UNIMPORTANT AT SHORT WAVELENGTHS

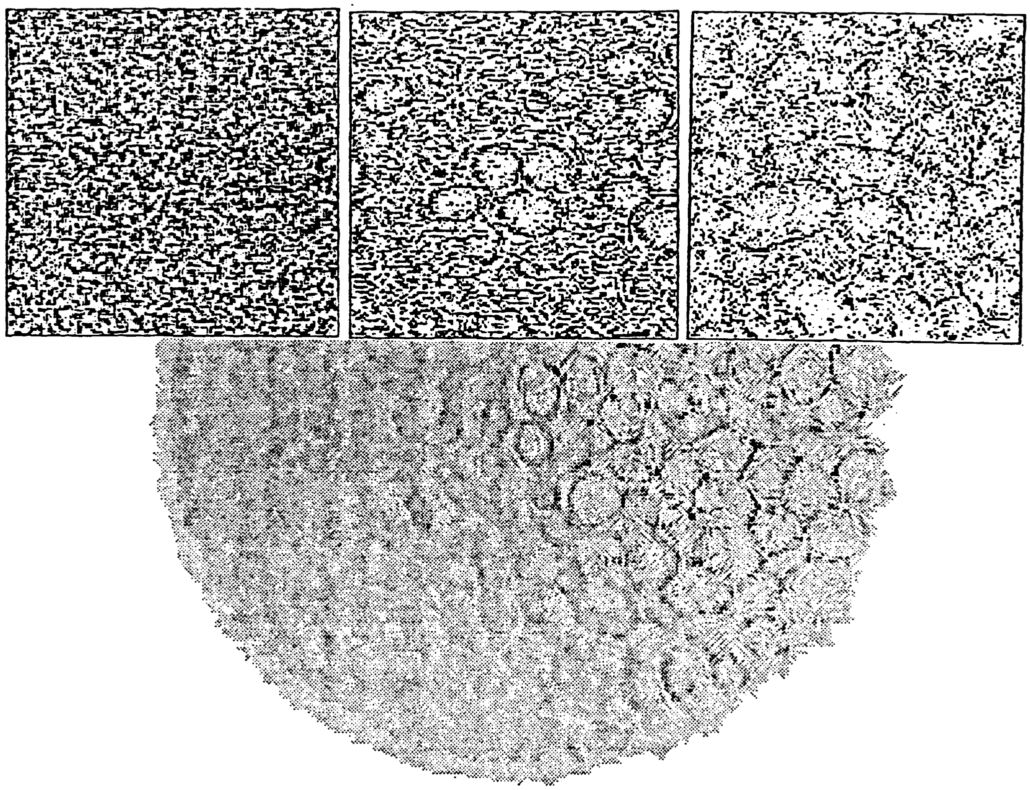
Wavelength	λ	0.41 μ	1.06 μ	10.6 μ
Whole Beam Fresnel number	N_F	2440	943	94
Turbulence Fresnel number	N_T	3.2	12.1	287

- The smaller the Fresnel number, the more important the effects.
- The actuator Fresnel number is generally of the order of the turbulence Fresnel number.
- At 1μ, turbulence induced small scale growth is the most important effect. A typical scale size is the scintillation scale, $\sqrt{\lambda L} \sim 3$ cm. This is much smaller than the nominal size of many beams of present interest.

ABERRATIONS CLUSTER AROUND A DISTINCT LENGTH SCALE



SMALL SCALE STRUCTURE CAN BE STUDIED IN A FRAME THAT CONVECTS WITH THE WIND



PATCH PHYSICS IS THE BASIS OF A COMPLETE THEORY

- Since the small scale physics controls beam quality of a high Fresnel number beam, the time dependence of the finite beam Strehl is a local property of the beam, not a global one.
- The edges of the beam only enter kinematically (i.e. fluid enters and exits the beam in a finite time).
- Therefore, the time development of the Strehl of an infinite beam or patch can be used to make finite or "whole" beam Strehl predictions.
- The patch Strehl, S_p, provides a very good estimate of the fraction of energy that contributes to the far field spot. From the definition of Strehl, it then follows that the whole beam Strehl, S, is

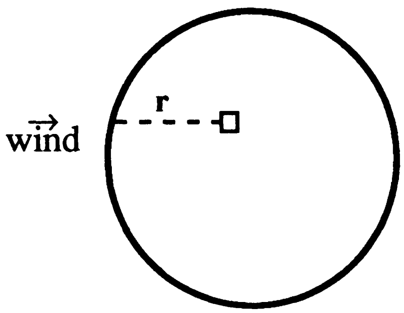
$$S = \left| \frac{\int d^2x \, S_p(\varphi(x))^{1/2} \, I^{1/2}(x,0)}{\int d^2x \, I^{1/2}(x,0)} \right|^2$$

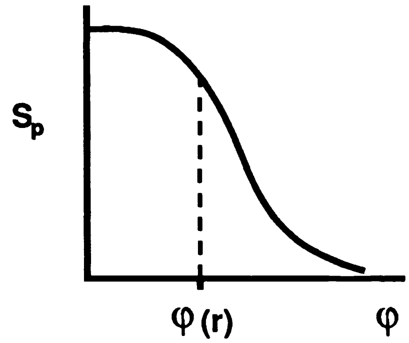
METHODOLOGY OF PATCH RECONSTRUCTION

- To predict the Strehl of the whole beam as a function of time we need only calculate the Strehl of a patch as a function of (nondimensional) time, ϕ = radians of blooming.

- To complete the computation we only need to compute the number of radians of blooming at each point of the whole beam for the particular time of interest (e.g. at a wind clearing time).

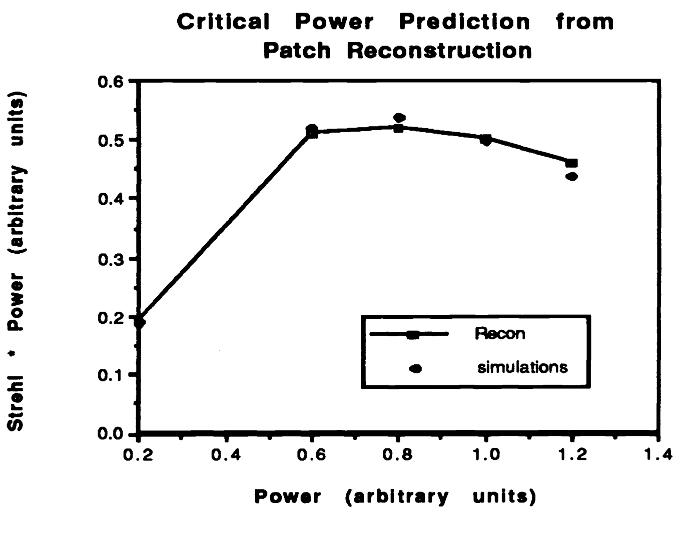
- As a simple example, consider a case where the atmosphere and heating profile are uniform. Then $\phi = \Gamma IkLt$. The t associated with the patch a distance r into the beam is the time the patch has spent in the beam, $t = r/v$, v = background wind velocity. Thus $\phi = \Gamma IkL\,|\vec{x}|/v$.





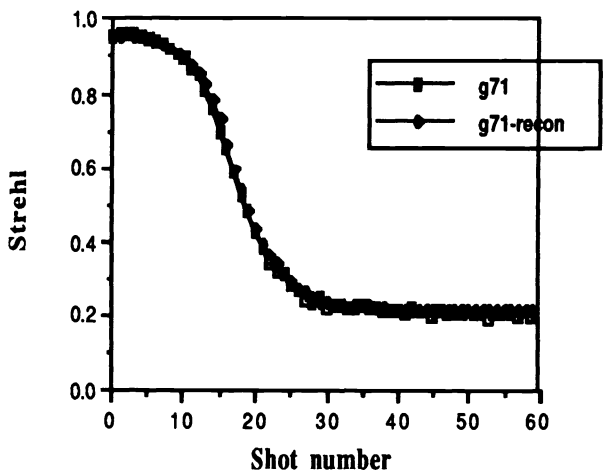
CRITICAL POWER CAN BE PREDICTED WITHOUT REFERENCE TO WHOLE BEAM EFFECTS

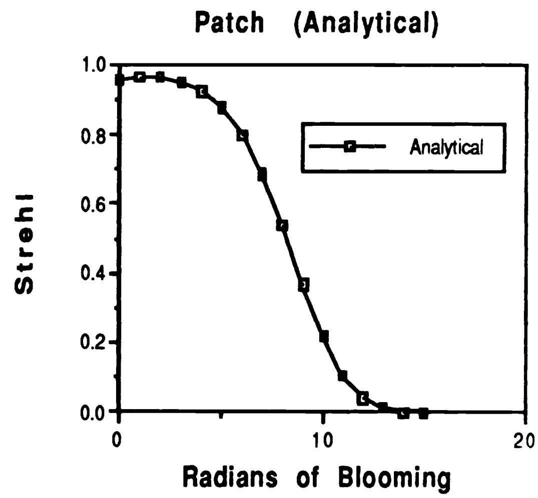
- The curve labeled "recon" is a set of critical power predictions of a 1.4 m beam in a nonuniform atmosphere with a slew rate of 1 mrad/sec, based on *one* patch simulation only. The other points are whole beam PHOTON simulations.



THE PATCH STREHL CAN BE CALCULATED ANALYTICALLY

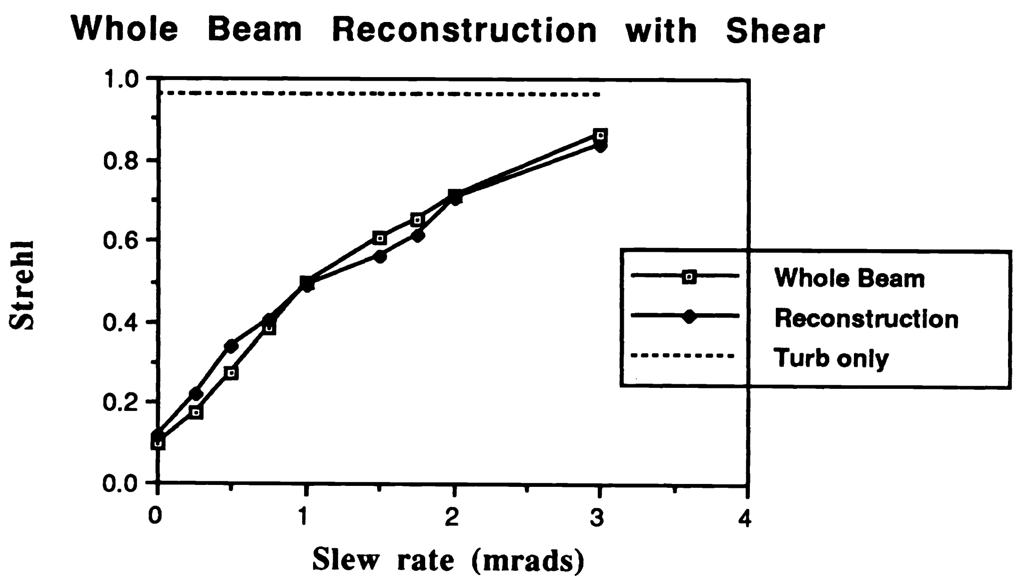
- g71 is a whole beam simulation through a uniform atmosphere with a constant wind. The patch calculation is based on the analytical results of the linear theory. Thus, the reconstructed whole beam Strehl is an analytical prediction that involves *no* simulations. The reconstruction is clearly successful.





UNIDIRECTIONAL, NONUNIFORM WIND

- Patch reconstruction correctly predicts Strehl at wind clearing time in the presence of slew.



PATCH RECONSTRUCTION FOR NON-UNIDIRECTIONAL WIND

- For a general, non-unidirectional wind, $\varphi(\mathbf{x}) = \int dz \frac{\partial\varphi}{\partial z}(\mathbf{x})$. The heating profile, $\frac{\partial\varphi}{\partial z}(\mathbf{x})$, for the point $\mathbf{x}$ in the finite beam may be computed from integrating the heating equation ($k\delta n_B = \frac{\partial\varphi}{\partial z}$),

$$\frac{D}{Dt}\frac{\partial\varphi}{\partial z} = -k\,\Gamma(z)\,I(z),$$

where $\frac{D}{Dt}$ is the convective derivative.

- For a non-unidirectional wind, every point in the beam has a different heating profile. The patch should have the same heating profile, but this is not practical.

- Instead, we take the following viewpoint. The patch Strehl is a functional on the space of all heating profiles (the space of real functions on the interval z=0 to z=L), which for the patch is identical to the space of absorption profiles.

PATCH RECONSTRUCTION FOR NON-UNIDIRECTIONAL WIND (cont'd)

- For small heating, the functional map of absorption profiles into the Strehl is quadratic in the absorption profile and provides for a metric on the function space.

$$\ln S = -0.093\,(N_T)^{-5/6}\,A_{11}\,\phi^2$$

$$A_{11} = \langle\alpha|\mathbf{F}|\alpha\rangle.$$

- Switch to a basis $|\alpha_i\rangle$ in the space of absorption profiles that diagonalizes **F**. The eigenvector $|\alpha_0\rangle$ that yields the largest eigenvalue will give the largest contribution to A_{11}, and, in fact, dominates the contribution from the other eigenvectors.

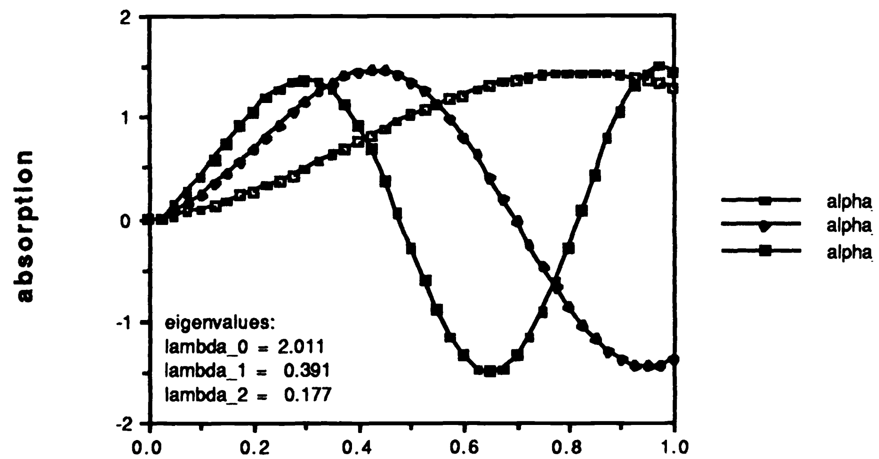
- We need only perform patch calculations corresponding to the first few eigenvectors to reconstruct any realistic heating conditions since we can expand the actual heating profile in the whole beam in the eigenvector basis.

$$|\frac{\partial\varphi}{\partial z}\rangle = \langle\alpha_0|\frac{\partial\varphi}{\partial z}\rangle\,|\alpha_0\rangle + \langle\alpha_1|\frac{\partial\varphi}{\partial z}\rangle\,|\alpha_1\rangle + \ldots$$

PATCH RECONSTRUCTION FOR NON-UNIDIRECTIONAL WIND (cont'd)

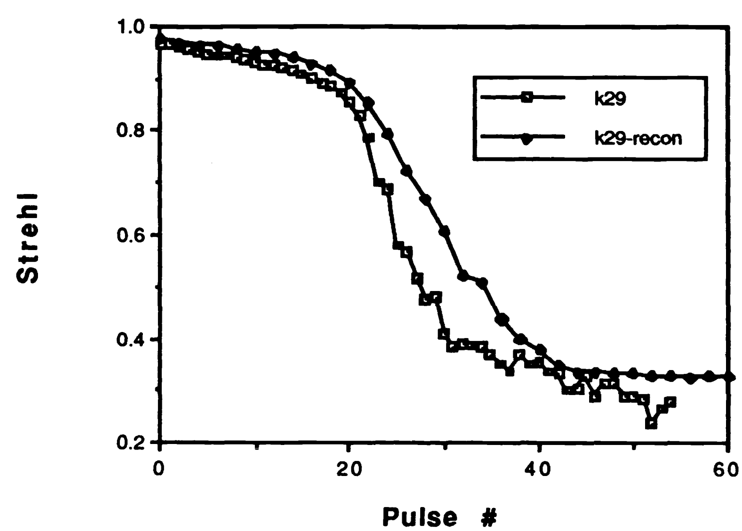
- The contribution of the eigenpatch Strehl S_{pi}, for the i^{th} eigenvector to the estimate of U at the point of the whole beam will then be determined by a total heating that is proportional to the overlap, $\langle \alpha_i | \frac{\partial \varphi}{\partial z} \rangle$.

Absorption eigenprofiles for SLCday



PATCH RECONSTRUCTION FOR NON-UNIDIRECTIONAL WIND (cont'd)

- k29 is a 1.4 m whole beam simulation through SLCday turbulence with a slew rate of 2 mrads/sec that is perpendicular to a uniform background wind. This reconstruction is based on a *single* patch where the absorption profile is $|\alpha_0\rangle$, max eigenvalue profile for SLCday.



SCALING FOR HIGH FRESNEL NUMBER BEAMS

- In general, the patch Strehl appropriate to a point in the beam is a function of three functions: the heating profile $\partial\phi/\partial t$, the heating rate profile $\partial^2\phi/\partial z\,\partial t$, and the shearing profile, $\partial v/\partial z$.

- In the absence of wind shear, high Fresnel number beams scale as Power/Diameter (P/D) for a given atmosphere, since the patch Strehl depends only on the heating profile.

- The effects of wind shear (and of slew) scale with intensity (P/D^2), so the patch Strehl in the presence of wind shear will depend on both the heating profile and the heating *rate* profile. Techniques for interpolating on the hearing *rate* profile are similar to these for interpolating on the heating profile.
5

- Scaling for high Fresnel number beams must be P/D^n where $1 \leq n \leq 2$. P/D^2 scaling would obtain *only* if there were complete suppression of small scale growth.

- The actual scaling that applies will depend on the details of the shearing profile, $\partial v/\partial z$. Which of these details are important is not well understood.

CONCLUSION

- The performance of high Fresnel number beams can be predicted from analytical or computational predictions for infinite Fresnel number beams.

- The growth of small scale structure governs the performance of high Fresnel number beams. The essential physics are both local and linear.

- Scaling in the absence of wind shear is P/D. Wind shear can make the scaling no better than P/D^2.

- The best way to learn about scaling in the presence of the actual wind shear will be through experiments in the actual atmosphere over the actual propagation path.