

Wave Propagation through Random Media

A “random medium” is one where the wave speed is a random function of position.

This usually means:

- Random in space and time.
- Internally rearranging
- Bulk flow (i.e. wind, advection)

But it may mean anything...

Many common assumptions and conditions might not be true.

For example: *Stationarity, Gaussian, Poisson, equilibrium, ergodic*, etc.

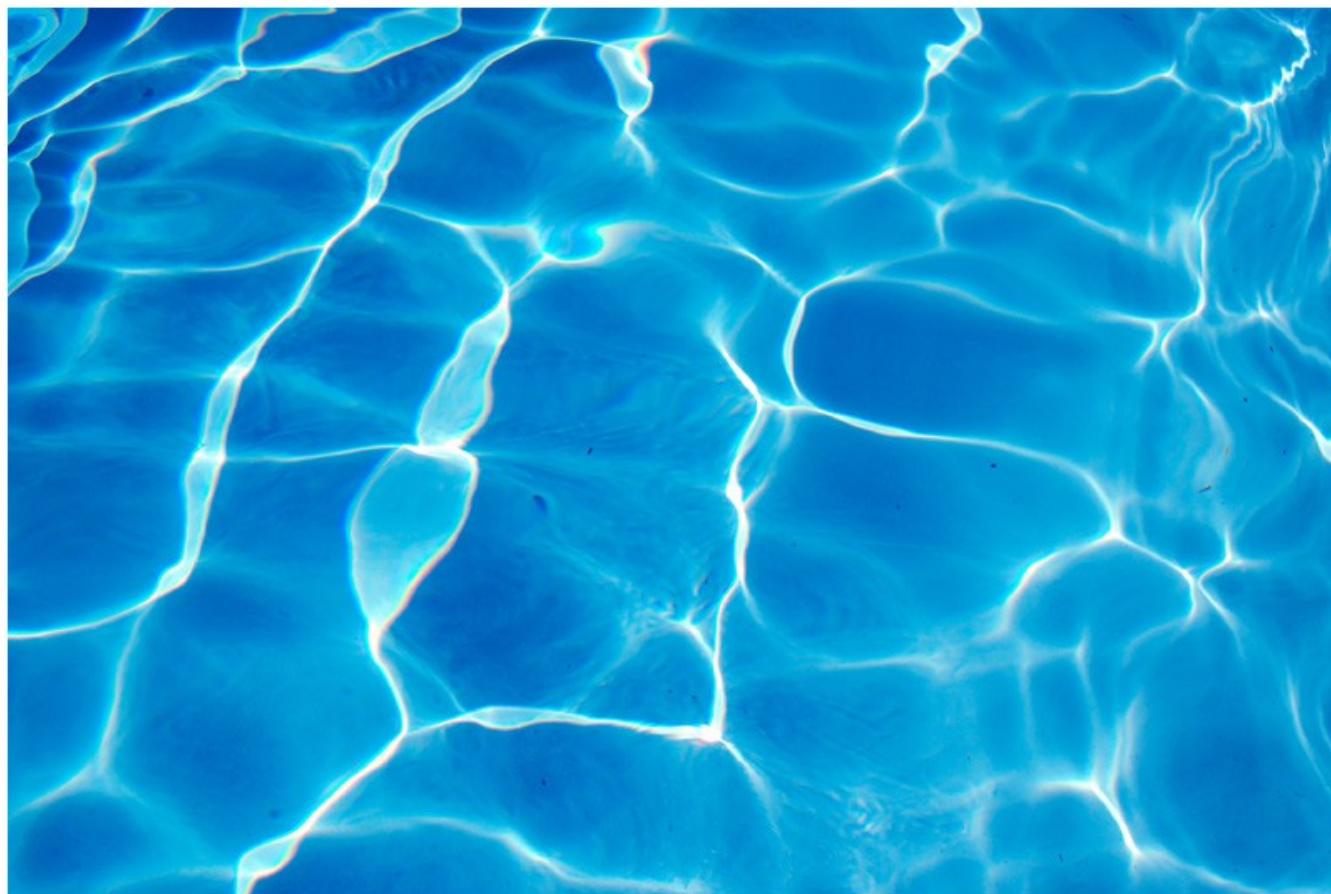
Just keep an open mind.

Wave Propagation through Random Media

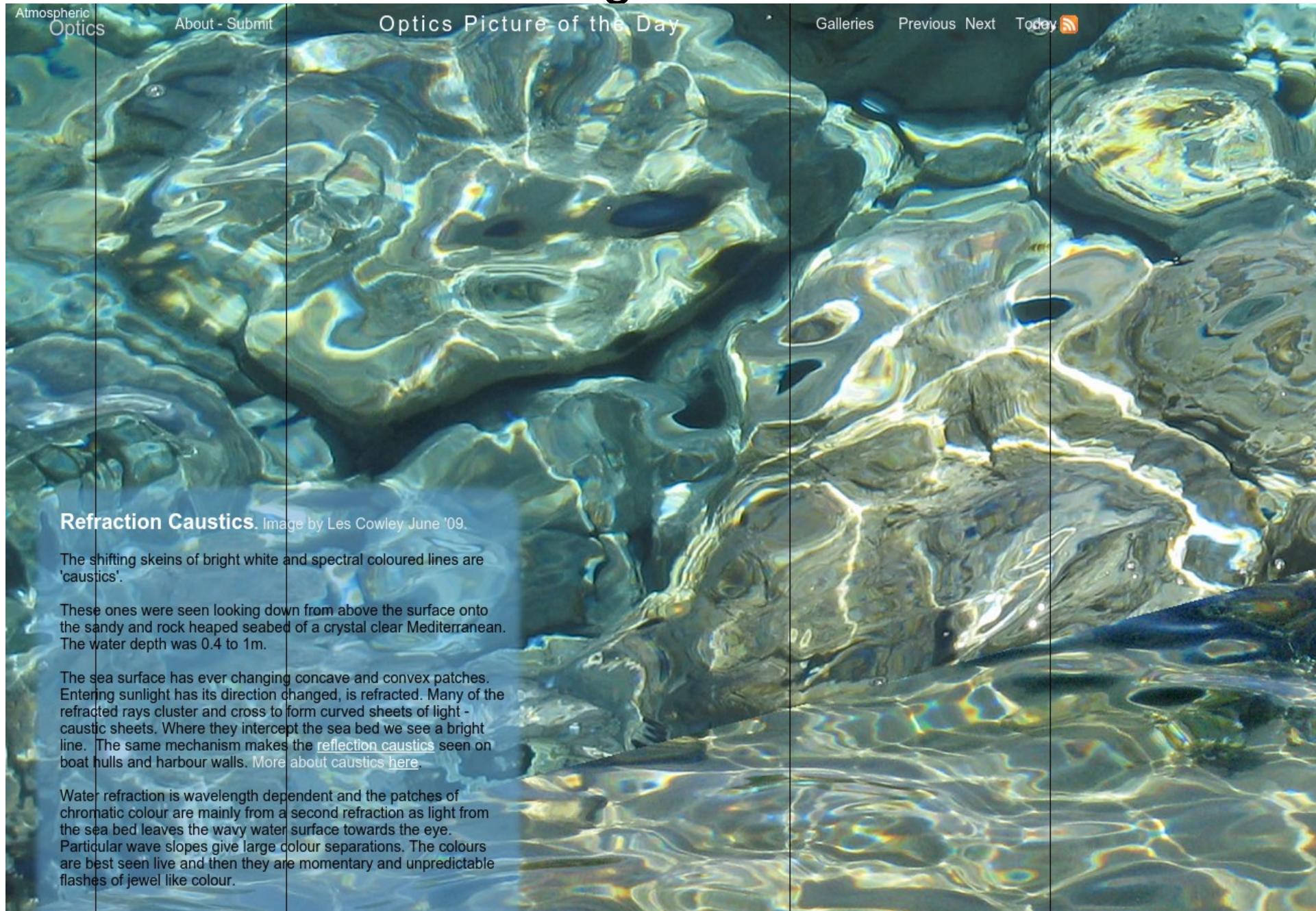
The index of refraction, $n(x,y,z,t)$, will usually be continuous and smooth in this course, but not always.

- Atmospheric turbulence (e.g. seeing and scintillation)
- Rain, fog, snow, hail, dust, etc. (Even large rocks as in distant starlight through a planetary ring system or a stellar debris disk.)
- Transmission or reflection through a fluctuating interface (swimming pool caustics, rough surface scattering)
- Non-isotropic media (ice crystals, magnetized plasma, phonons in crystals, etc.)
- Sound waves compressing optical fiber or other waveguide.
- Light or ultrasound through tissue and blood.
- Layered or structured media (e.g. mirages, fiber optics, ionosphere, ocean SOFAR channel, ...)
- Distant quasars seen through the Universe of small gravitational lenses.

WPRM Phenomena



Random Surface Image Distortion and Caustics



The image shows a close-up view of the ocean surface, characterized by intricate patterns of light and color. These patterns are created by sunlight passing through the water and being refracted as it passes through random surface fluctuations. The result is a complex web of bright white and spectral-colored lines (rainbow hues) that appear to float in the water. The background is a deep blue, and the overall effect is one of natural, shimmering beauty.

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Refraction Caustics. Image by Les Cowley June '09.

The shifting skeins of bright white and spectral coloured lines are 'caustics'.

These ones were seen looking down from above the surface onto the sandy and rock heaped seabed of a crystal clear Mediterranean. The water depth was 0.4 to 1m.

The sea surface has ever changing concave and convex patches. Entering sunlight has its direction changed, is refracted. Many of the refracted rays cluster and cross to form curved sheets of light - caustic sheets. Where they intercept the sea bed we see a bright line. The same mechanism makes the [reflection caustics](#) seen on boat hulls and harbour walls. More about caustics [here](#).

Water refraction is wavelength dependent and the patches of chromatic colour are mainly from a second refraction as light from the sea bed leaves the wavy water surface towards the eye. Particular wave slopes give large colour separations. The colours are best seen live and then they are momentary and unpredictable flashes of jewel like colour.

Refractive Image Distortion

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Trout and Optical Catastrophes

Imaged by Andrew Kirk. *"I was photographing rapidly moving caustics and a dead tree on the bottom of a wide stream, when a trout floated into the frame. I then began to attempt to catch the caustics as they crossed the trout. The distortions of the trout were too rapid to see, but the camera caught them!"* ©Andrew Kirk, shown with permission.

Random Surface Reflection

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Reflection Caustics & Skypools. Image by Les Cowley June '09.

The dazzling sharp white patterns on the fishing boat hull are 'caustics' generated by sunlight reflected from the undulating sea surface.

Why are there well defined lines rather than fuzzy patches of light? Sun rays reflected from the surface cluster and cross to form sheets of light. Where the otherwise invisible caustic sheets intercept a surface like the boat hull they produce bright lines. The wave shapes produce paired sheets evidenced by the double lines on the hull with bright areas between them. *More about caustica and their geometry here.*

At lower right there are faint 'skypools'. Concave patches reflect the sky to towards the eye from their centres but reflect the harbour surroundings from their steeper edges. The result is oval patches of blue surrounded by the darker shore and boat colours.

Rough Surface Scattering

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Chromatic Glitter



Mila Zinkova ([site](#)) caught this towering horizon mirage and color fringed ocean glitter on Nov 15, '08 from Pigeon Point Lighthouse about 60 miles south of San Francisco. She was 10-20 ft above the sea level. ©Mila Zinkova, shown with permission.

The cold ocean has produced a temperature inversion, cool air trapped below warmer, ideal for superior mirage and even Fata Morgana formation. Here we are seeing not a mirage of the sun (which was 15° high) but of the glints from the undulating ocean surface. Each glint acts as an individual source of light which is refracted and miraged by the intervening air. The upper blue-green edge to the mirage arises from the stronger refraction of green and blue rays compared with red (dispersion). Parts of the mirage also vertically magnify the color dispersion. The refraction is so strong that even the lower glints have upper green and lower red edges.

Scattering from Surface Waves



Lunar Glitter Path, Lake Neuchâtel, Switzerland - Imaged by John Sergneri on March 13, 2009. ©John Sergneri, shown with permission.

Glitter patches (or paths) are the myriad of individual glints - instantaneous reflections of the moon or sun - from facets of the undulating and shifting liquid surface that happen at that moment to have the right position and tilt.

Glitter paths, GPs, seem to have horizontal striations but this tells us little about the wave directions. To create a path the waves do not need to be coming towards you. Foreshortening makes undulations of all sorts appear to have horizontal striations when they are viewed close to the horizon at shallow angles.



High-angle backscatter



Glory on Pinnacle Ridge, Pen yr Ole Wen, Wales photographed by John Hardwick in February 1993. It shows the classical appearance of a mountain glory as sunshine breaks through a mist. When the mist is nearby the glory is accompanied by your shadow. [Larger image](#). ©John Hardwick, reproduced with permission.



Glories can be predicted by Mie scattering calculations as used in IRIS. The matching simulation at upper left shows that the droplets were small, only 10 micron diameter.

Glories are always directly opposite the sun, centered at the antisolar point and therefore below the horizon except at sunrise and sunset.

Look for them whenever mist or cloud is beneath you and the sun breaks through to shine on it.

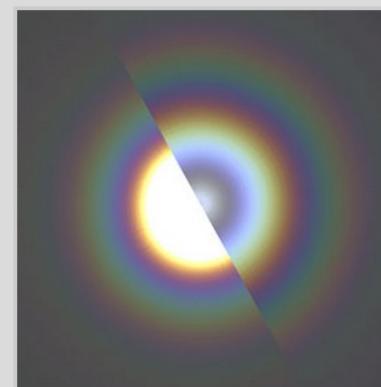
Glories can be seen on mountains and hillsides, from aircraft and in sea fog and even indoors.

They are formed when light is scattered backwards by individual water droplets.

They have a bright centre but not nearly as bright as the corona's aureole. Their rings are delicately coloured like those of the corona's, blue on the inside changing through greens to red and purple outside. The ring intensities fall off much more slowly than those of the corona and sometimes three or even four rings are visible.

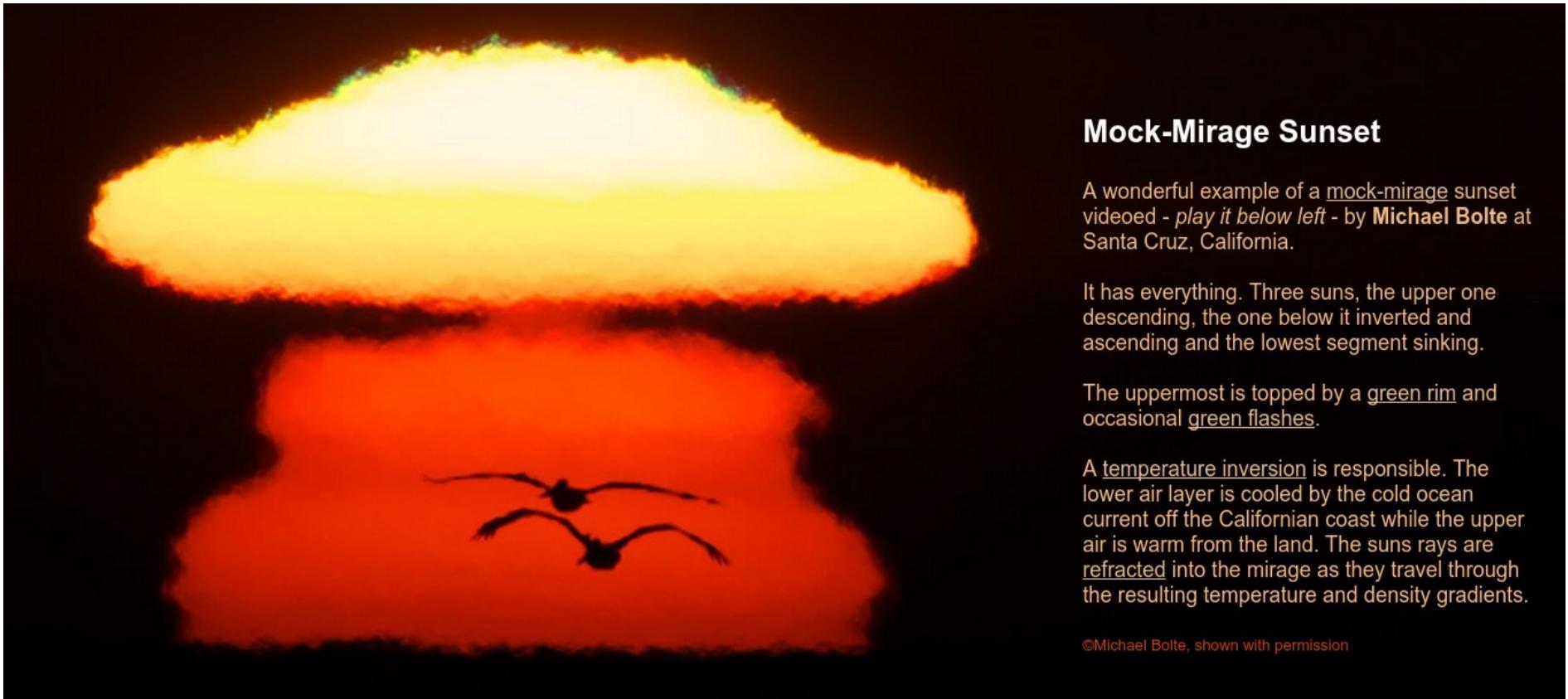
Shadows converge on the antisolar point and so glories are nearly always accompanied by your shadow or that of the aircraft you are in. When the shadow is grotesquely distorted by perspective it is called a "Brocken spectre".

There are other glows at the antisolar point, the heiligenschein and the opposition effect but these do not have the glory's shimmering rings.



Glory (right) and corona (left) for 20μm dia. droplets - IRIS simulations.

Refraction and multipath propagation



Mock-Mirage Sunset

A wonderful example of a mock-mirage sunset videoed - *play it below left* - by **Michael Bolte** at Santa Cruz, California.

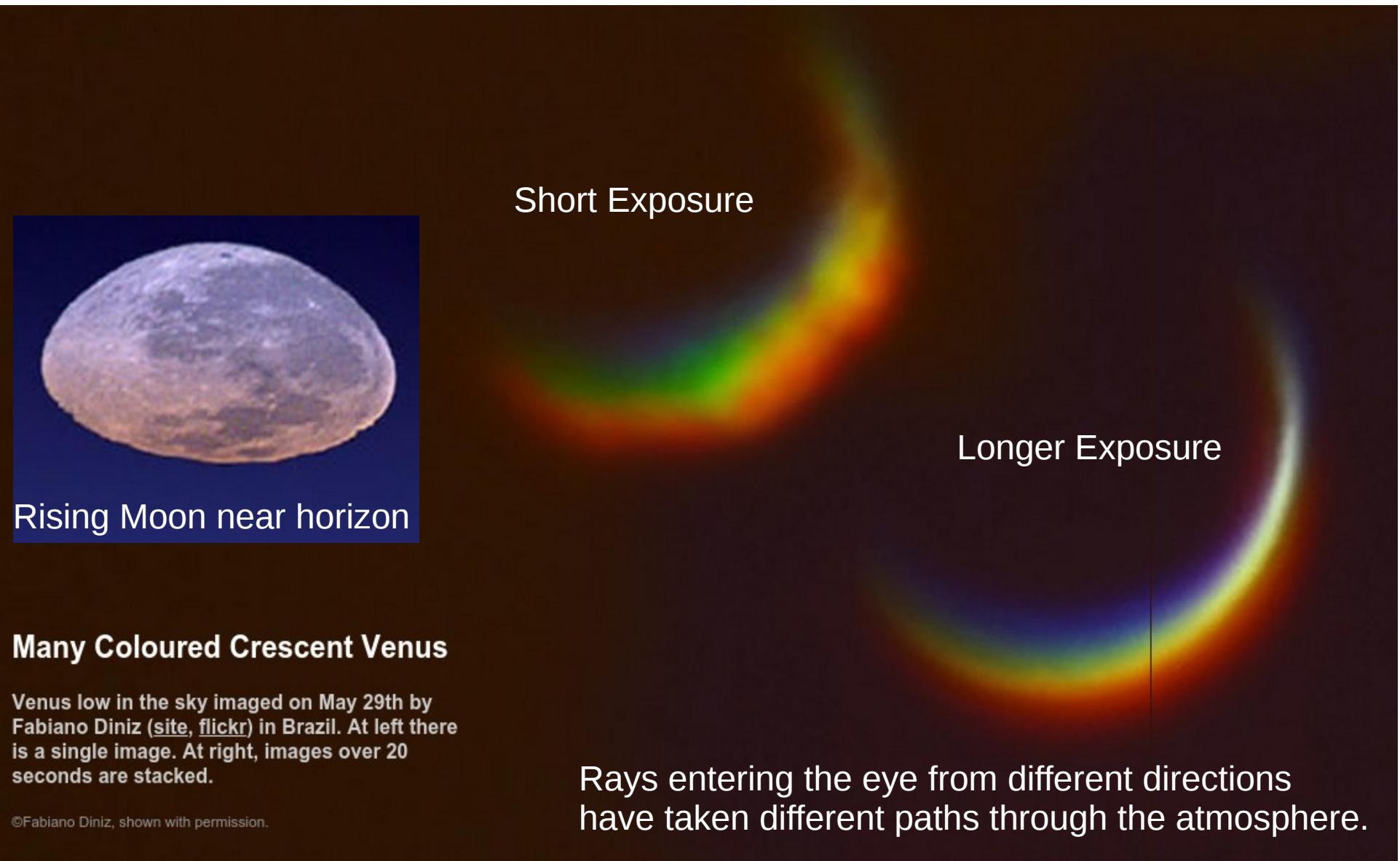
It has everything. Three suns, the upper one descending, the one below it inverted and ascending and the lowest segment sinking.

The uppermost is topped by a green rim and occasional green flashes.

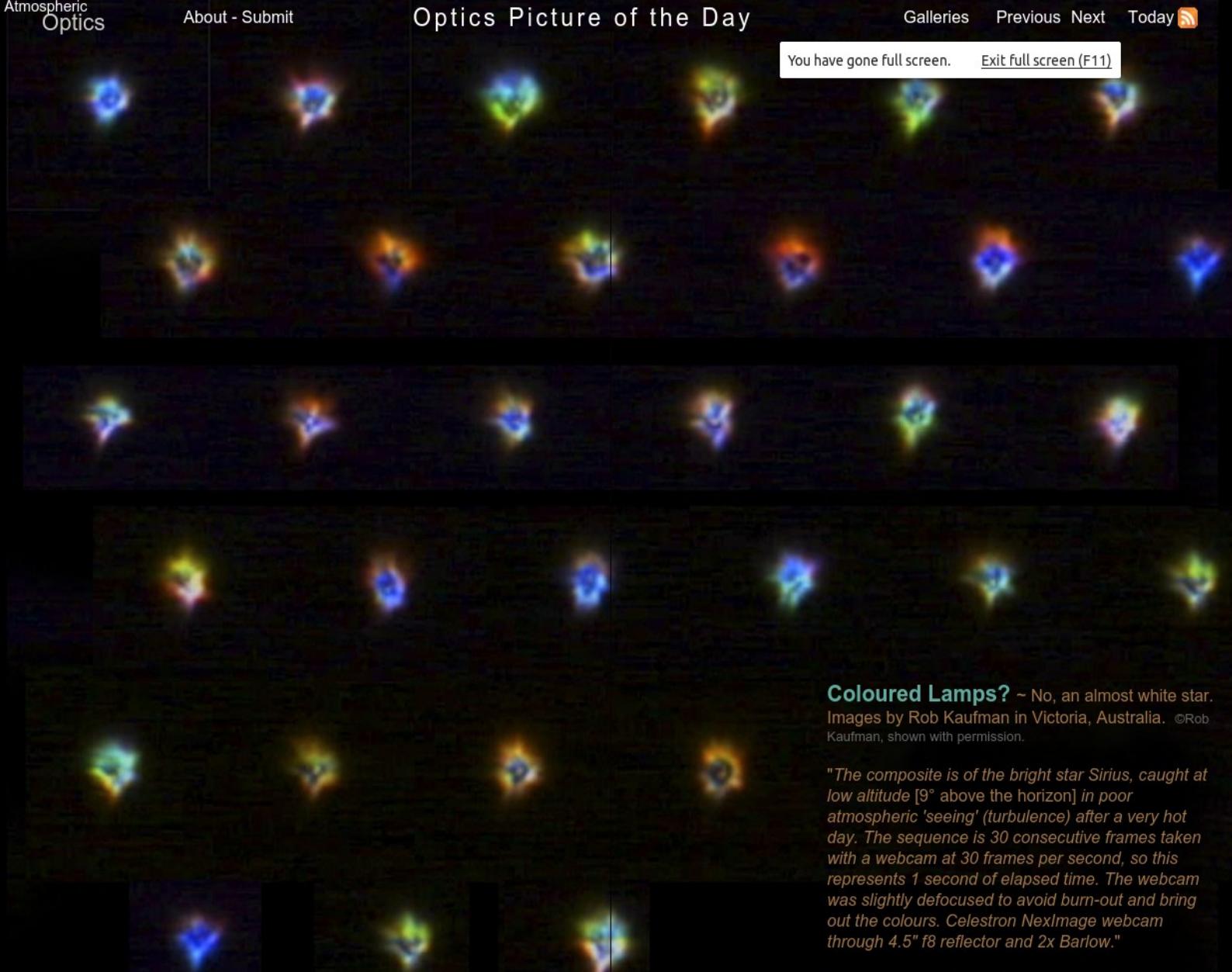
A temperature inversion is responsible. The lower air layer is cooled by the cold ocean current off the Californian coast while the upper air is warm from the land. The sun's rays are refracted into the mirage as they travel through the resulting temperature and density gradients.

©Michael Bolte, shown with permission

Atmospheric Refraction and Dispersion



Chromatic Scintillation



The image shows a 5x6 grid of star images, each exhibiting significant chromatic aberration. The stars appear as multi-colored, elongated shapes with distinct color gradients, ranging from blue at the core to red at the periphery. This visual effect is known as chromatic scintillation, where light from a single star is dispersed by varying atmospheric conditions, creating multiple images of the same star.

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You have gone full screen. [Exit full screen \(F11\)](#)

Coloured Lamps? ~ No, an almost white star.
Images by Rob Kaufman in Victoria, Australia. ©Rob Kaufman, shown with permission.

"The composite is of the bright star Sirius, caught at low altitude [9° above the horizon] in poor atmospheric 'seeing' (turbulence) after a very hot day. The sequence is 30 consecutive frames taken with a webcam at 30 frames per second, so this represents 1 second of elapsed time. The webcam was slightly defocused to avoid burn-out and bring out the colours. Celestron NexImage webcam through 4.5" f8 reflector and 2x Barlow."

Short exposure, out-of-focus star images.

Poor seeing, the bane of astronomers, is caused by the starlight passing through uneven and moving layers of air at different temperatures and therefore densities.

Chromatic Scintillation

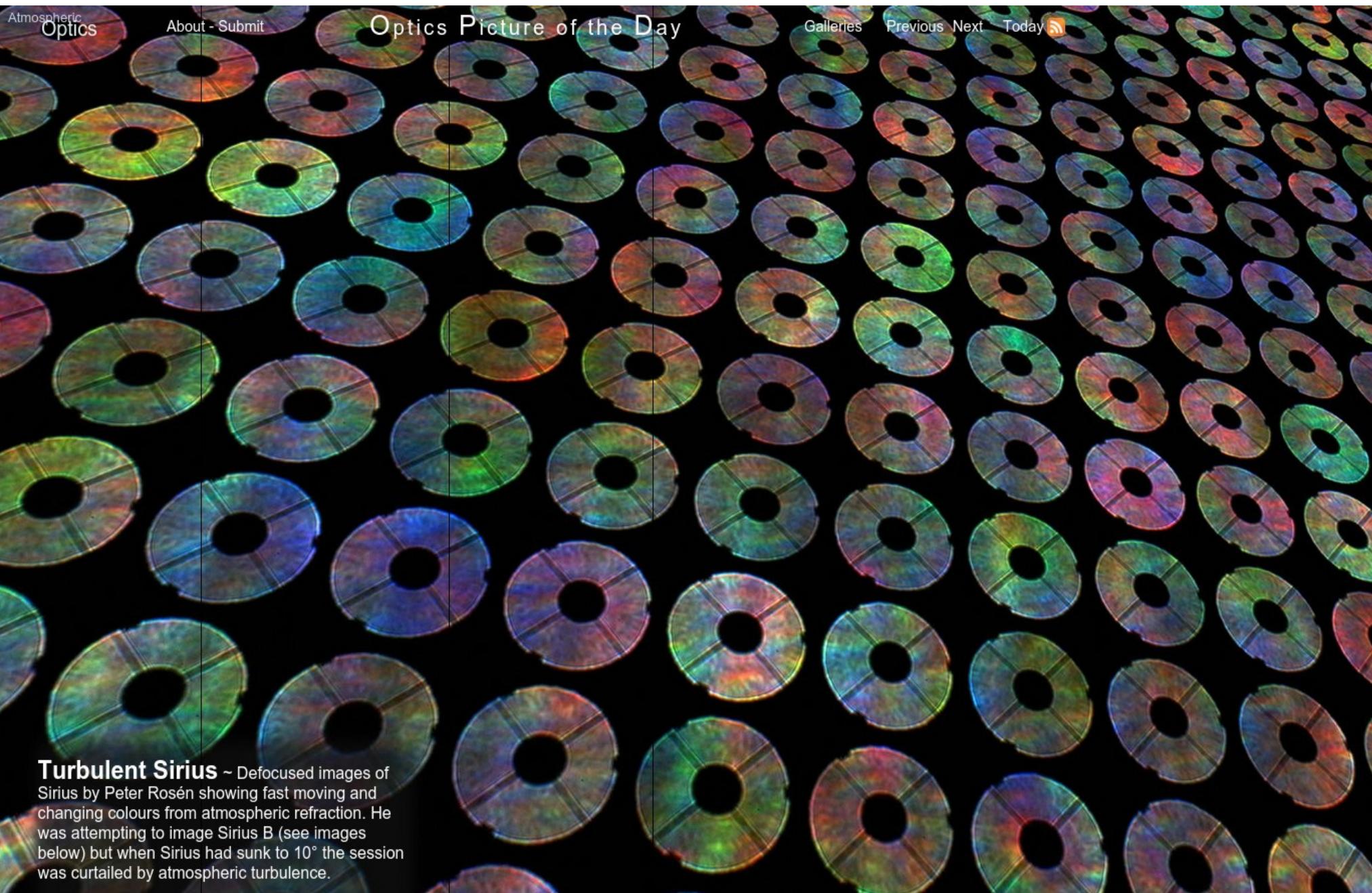
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Turbulent Sirius ~ Defocused images of Sirius by Peter Rosén showing fast moving and changing colours from atmospheric refraction. He was attempting to image Sirius B (see images below) but when Sirius had sunk to 10° the session was curtailed by atmospheric turbulence.

Evolution of Chromatic Scintillation

"At first I pushed the telescope during the exposure so it would start wobbling leaving a Lissajou-like colourful path that clearly shows the fast changing colours and luminance of scintillating Sirius.

This is nothing new as it has been done several times before but I took this image and superimposed it at the correct scale on one showing the star field. Canon Eos5D MkII and a 4x Televue Powermate on my CT-10, 250mm Newton from OrionOptics."

1



Chromatic Radio Scintillation in the Interstellar Medium

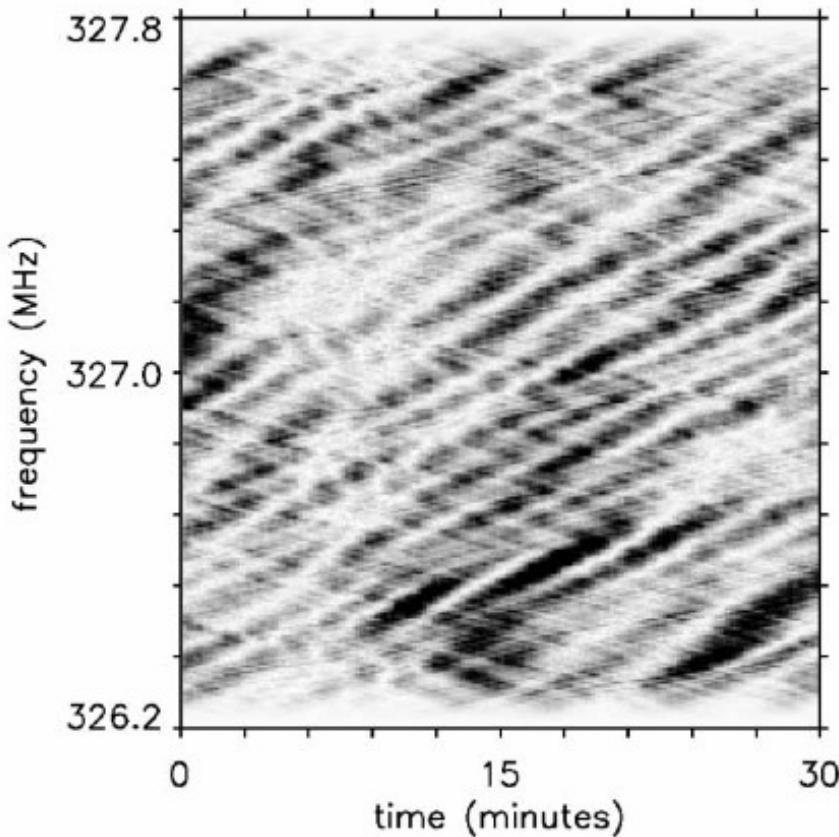


FIG. 1.—Dynamic spectrum of PSR B0834+06 observed on 2003 December 31. The flux density as a function of frequency and time is shown using a gray scale that is linear in power, with dark regions indicating high power. The criss-cross pattern is due to radio waves reaching the observer from a variety of angles (~ 10 mas away from the pulsar position), as detailed in the text.

Simulated ISS Dynamic Spectra

No. 2, 2010

SCATTERING OF PULSAR RADIO EMISSION BY THE INTERSTELLAR PLASMA

1209

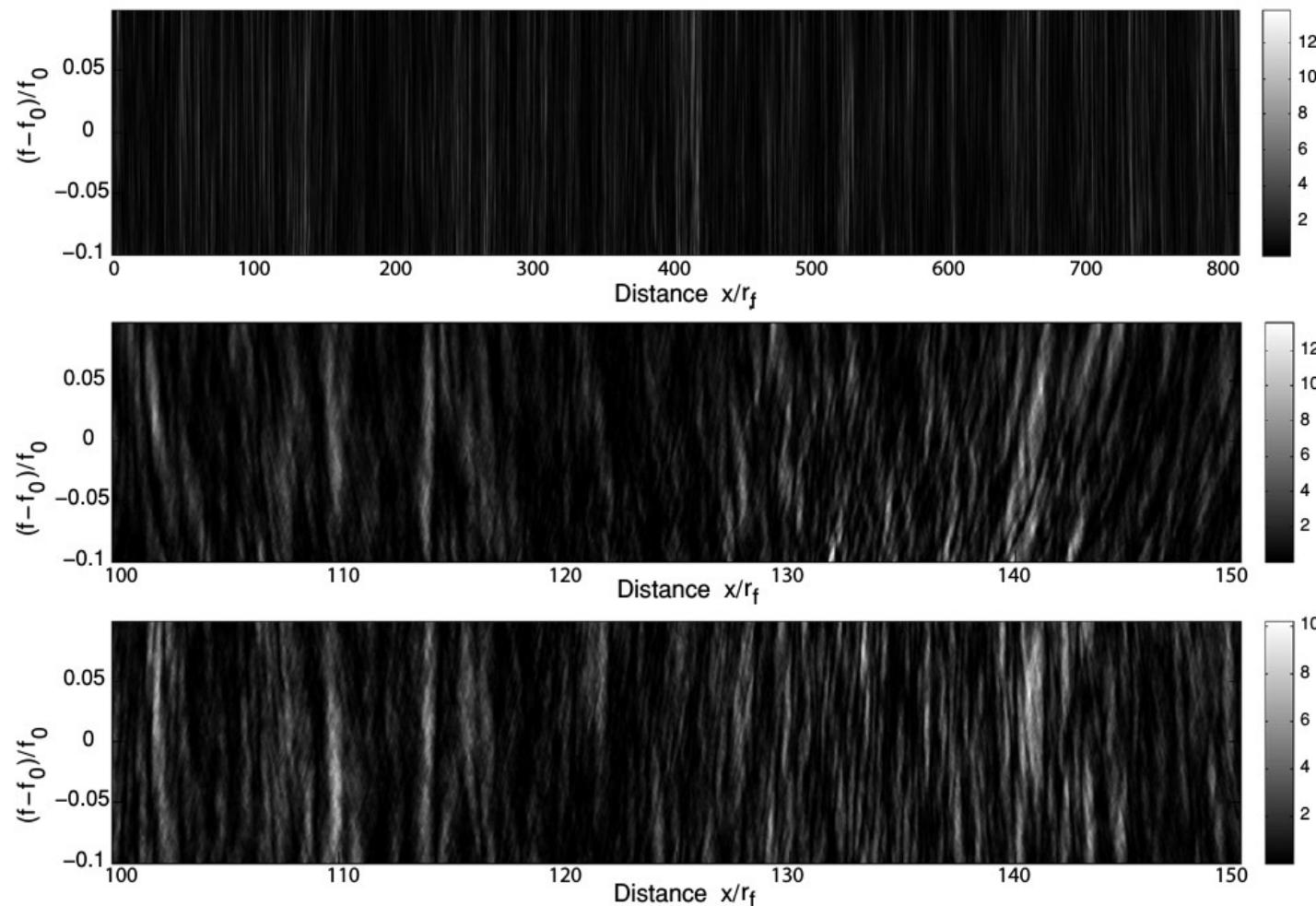
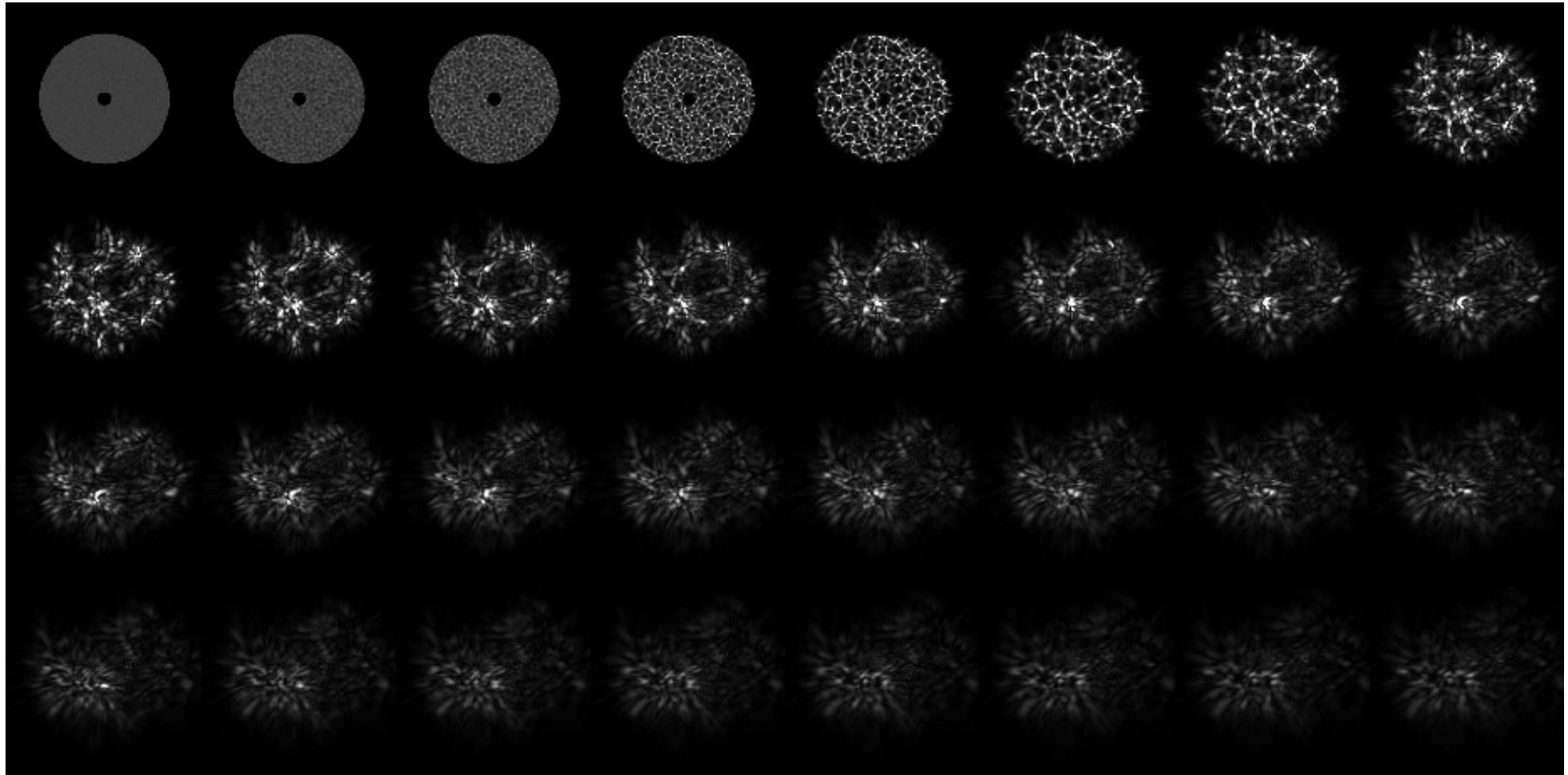
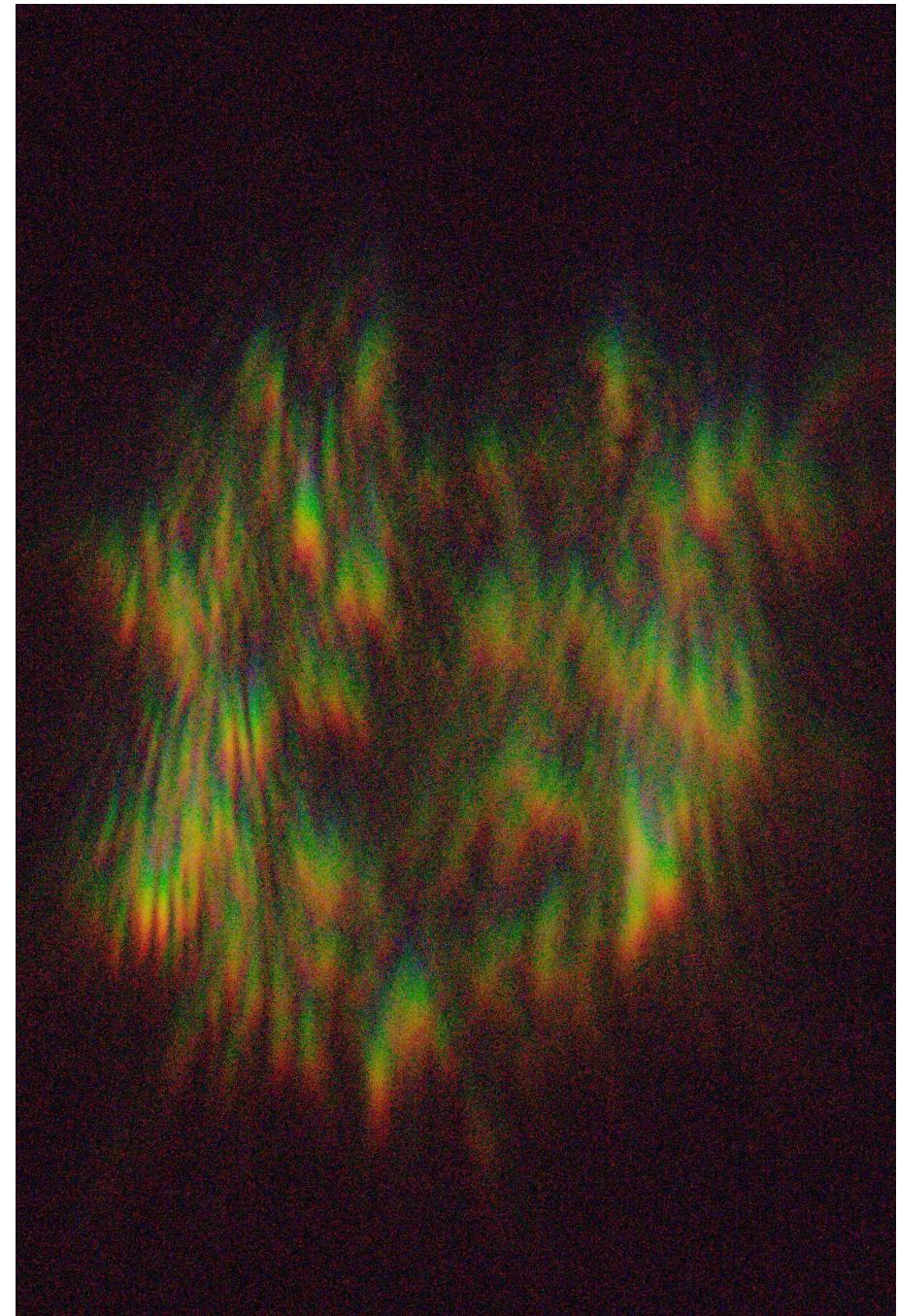
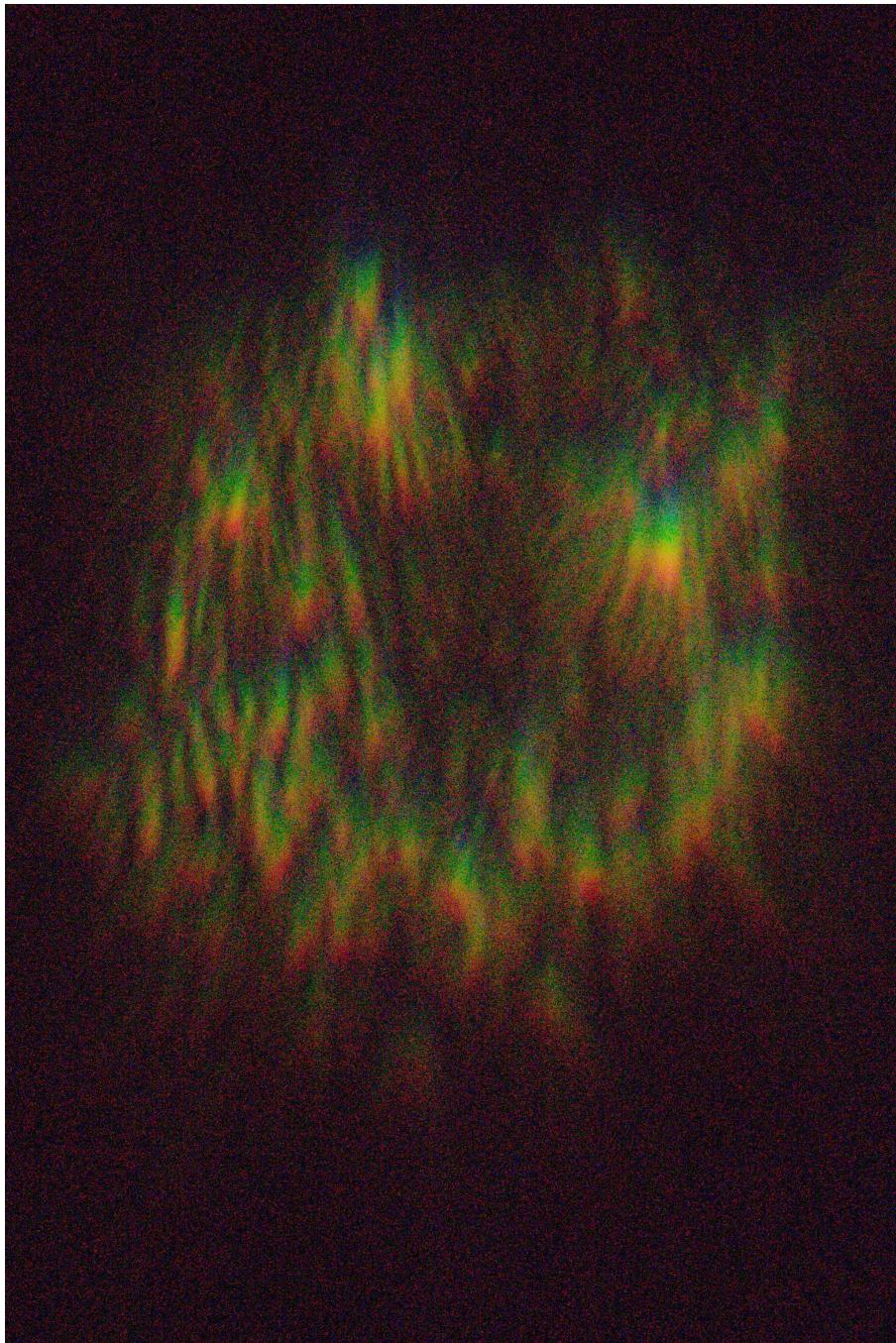


Figure 1. Dynamic spectra for $m_b^2 = 10$: (a) the top panel is the full dispersive simulation; (b) the middle panel is an expanded section of the top panel; (c) the bottom panel is the same as panel (b) except the simulation is run without dispersion. In each case, the abscissa is scaled with respect to the Fresnel scale r_f (about 3.2×10^5 km for a typical pulsar). If converted to a time axis using a velocity of 100 km s $^{-1}$, the full window corresponds to about a month of observation.

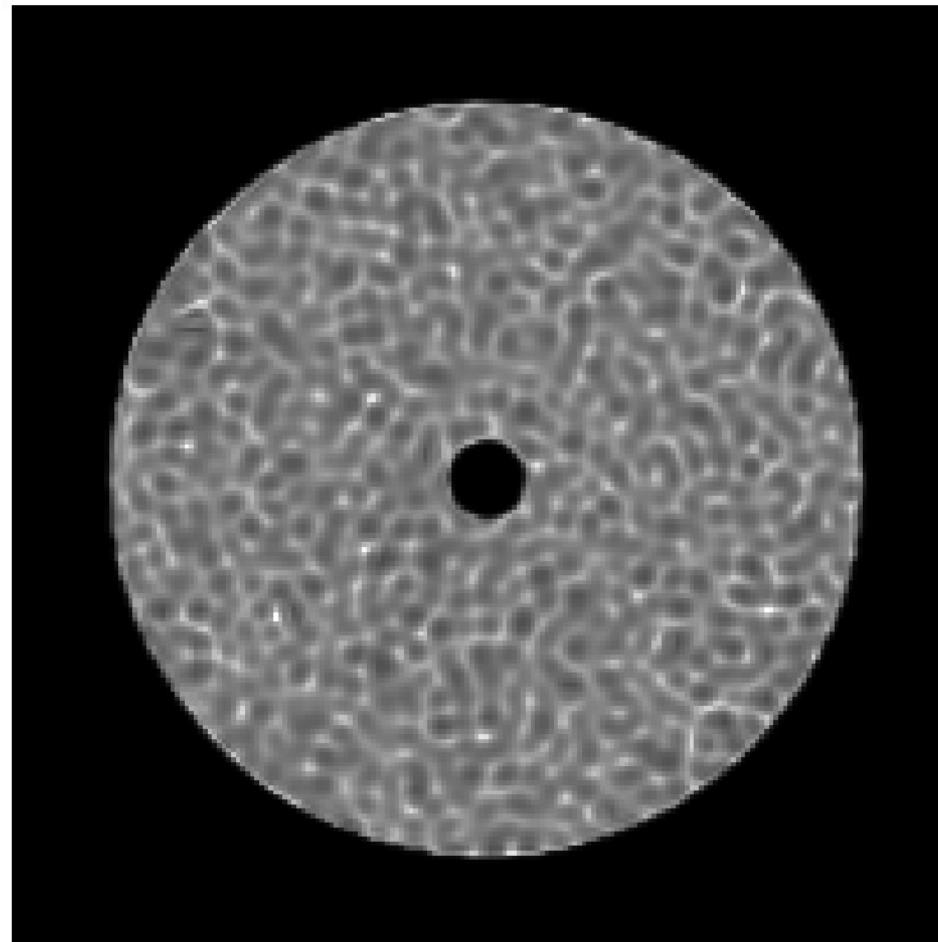
Evolution of Scintillation with Range



Defocused Star Images at the MMT

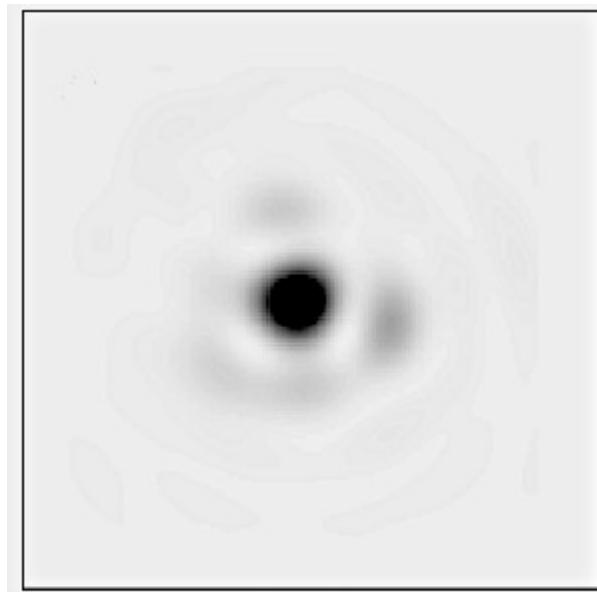
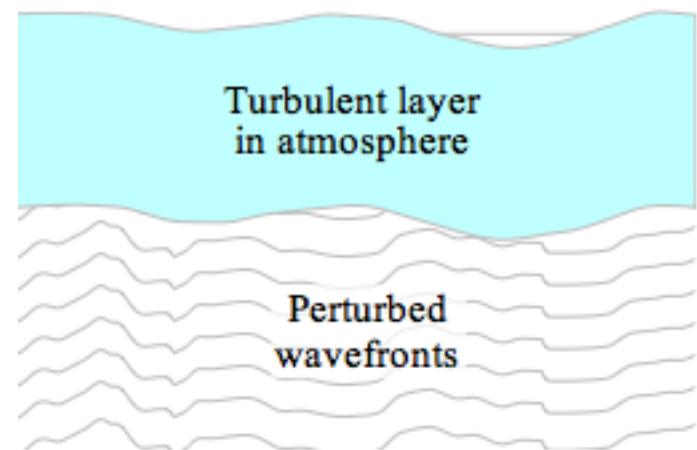


Weak Scintillation

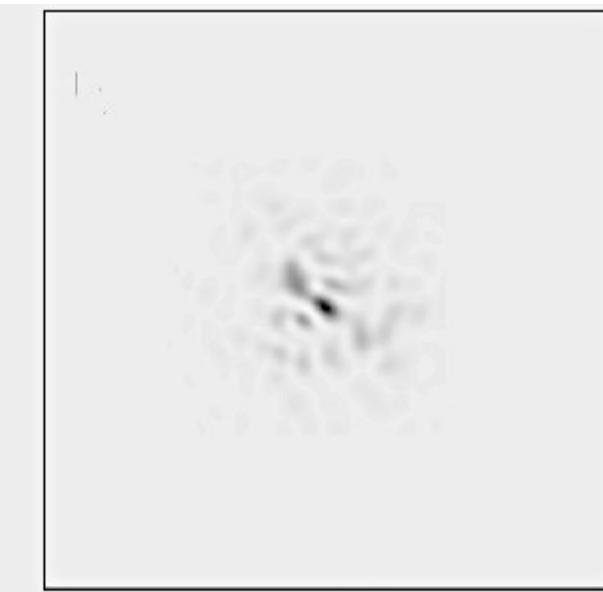


Images with Increasing Aperture

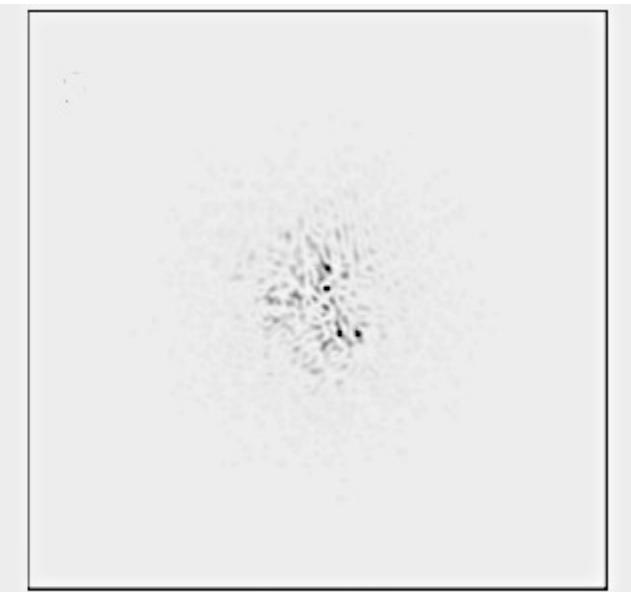
Plane waves from distant point source



$D=2r_0$
(8in telescope @ V, $r_0=10$)

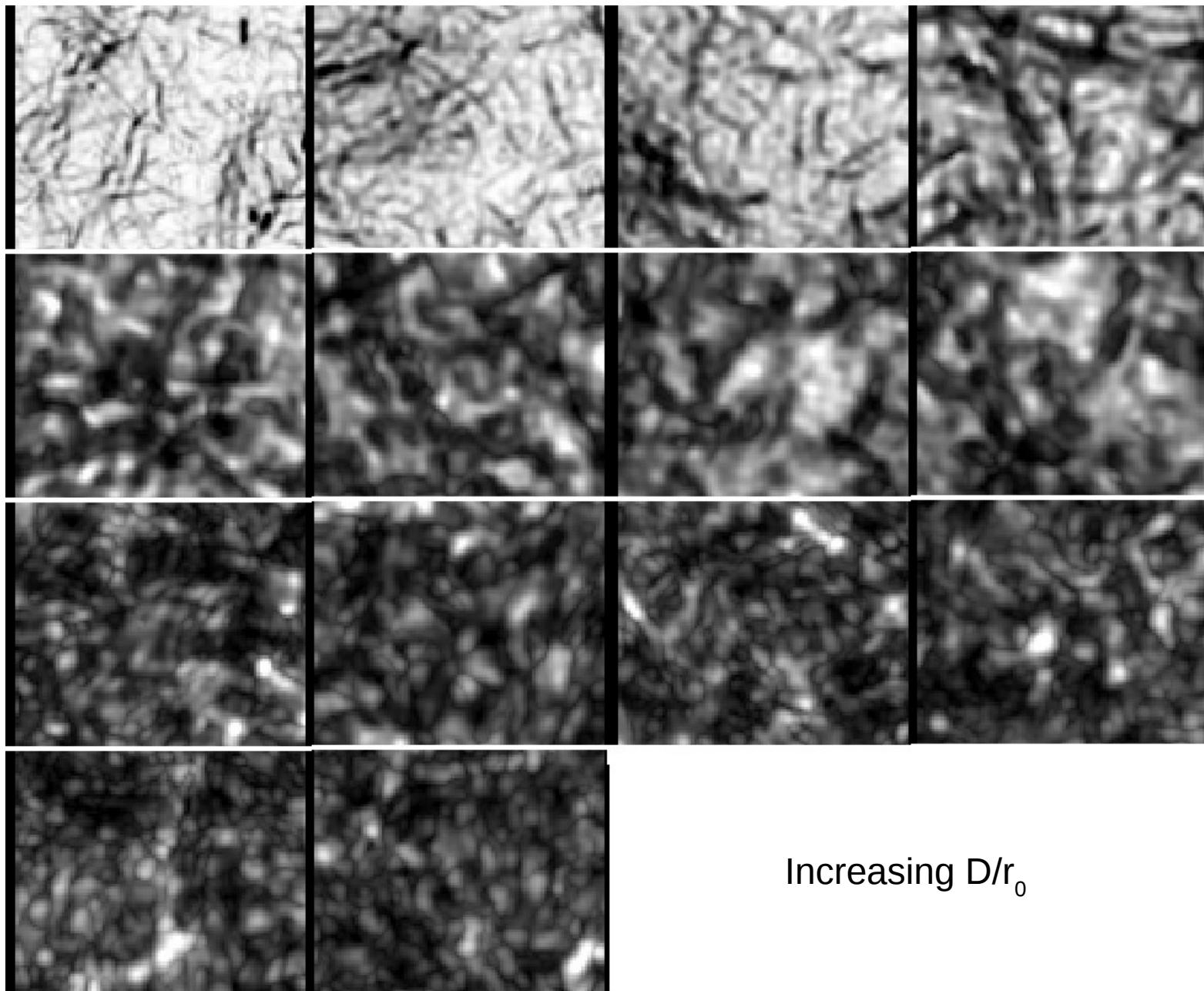


$D=7r_0$
(30in telescope @ V, $r_0=10$)



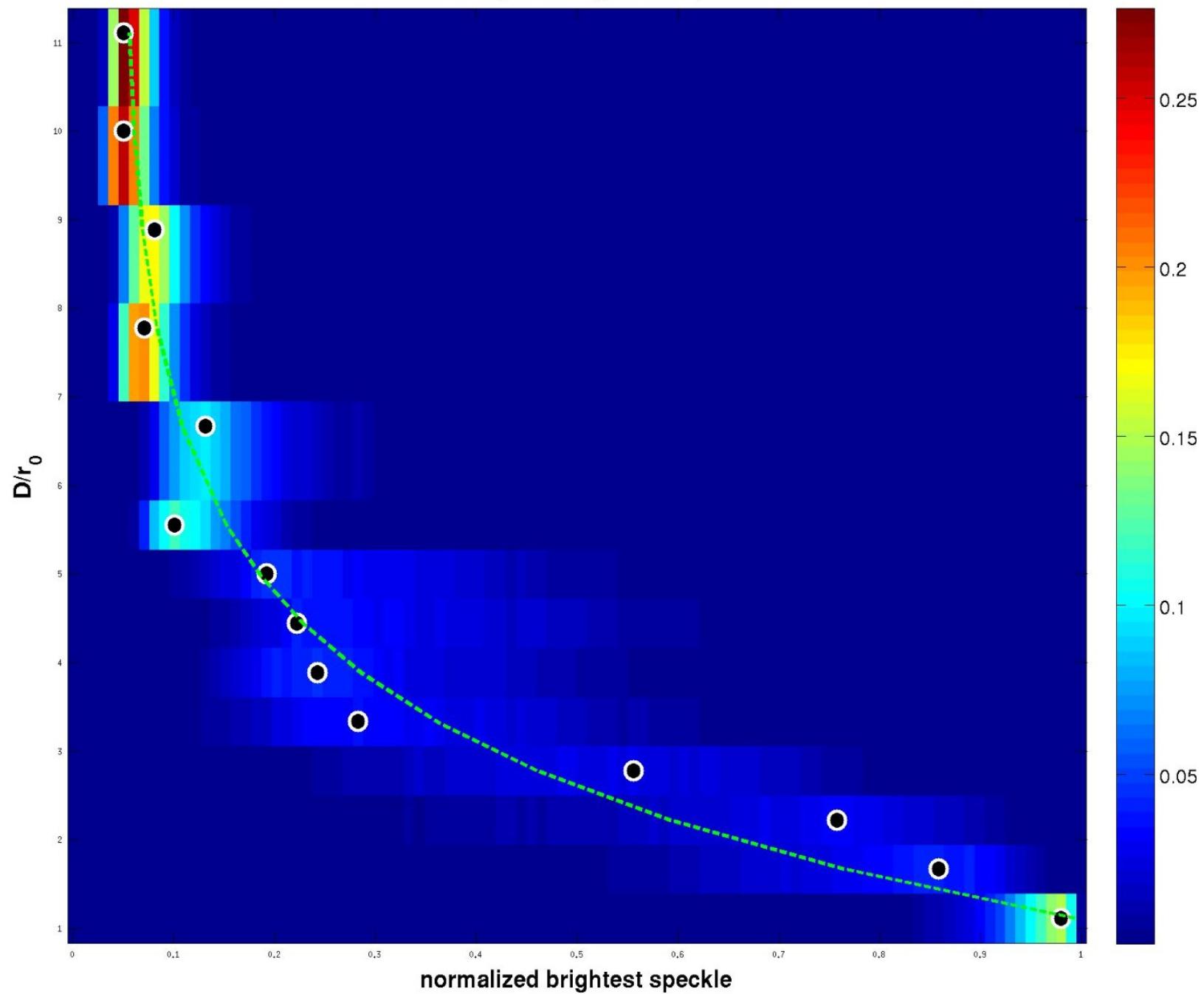
$D=20r_0$
(2m telescope @ V, $r_0=10$)

Brightest Speckle and Luckiness

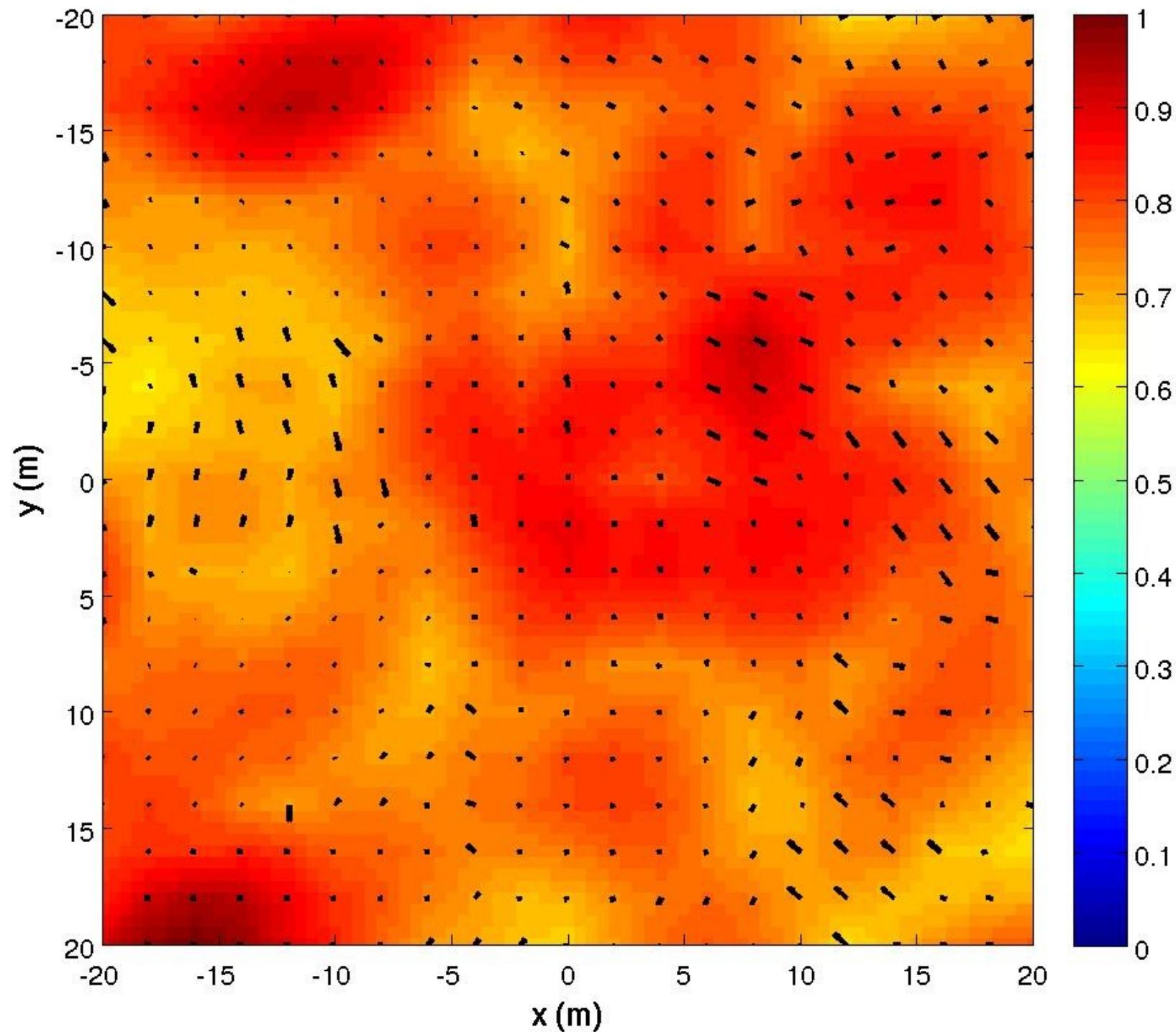


Lucky Imaging vs Scattering Strength

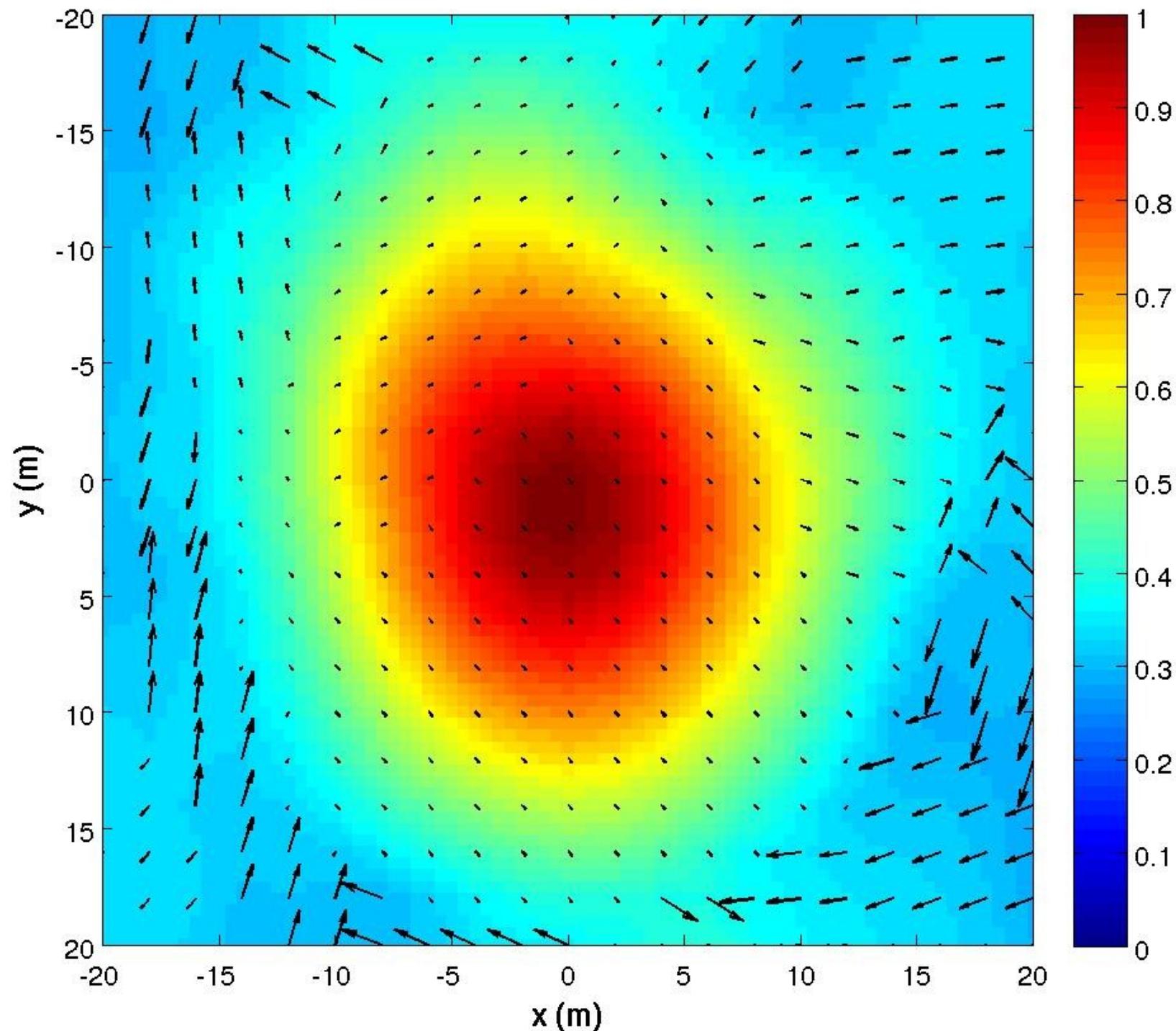
Probability of Brightest Speckle



Local Image Offset and Strehl at Orbit, t=-0.012 s



Local Image Offset (10x) and Strehl at Orbit, t=-0.136 s



The MMT AO System

This loop
is performed
at 550 Hz

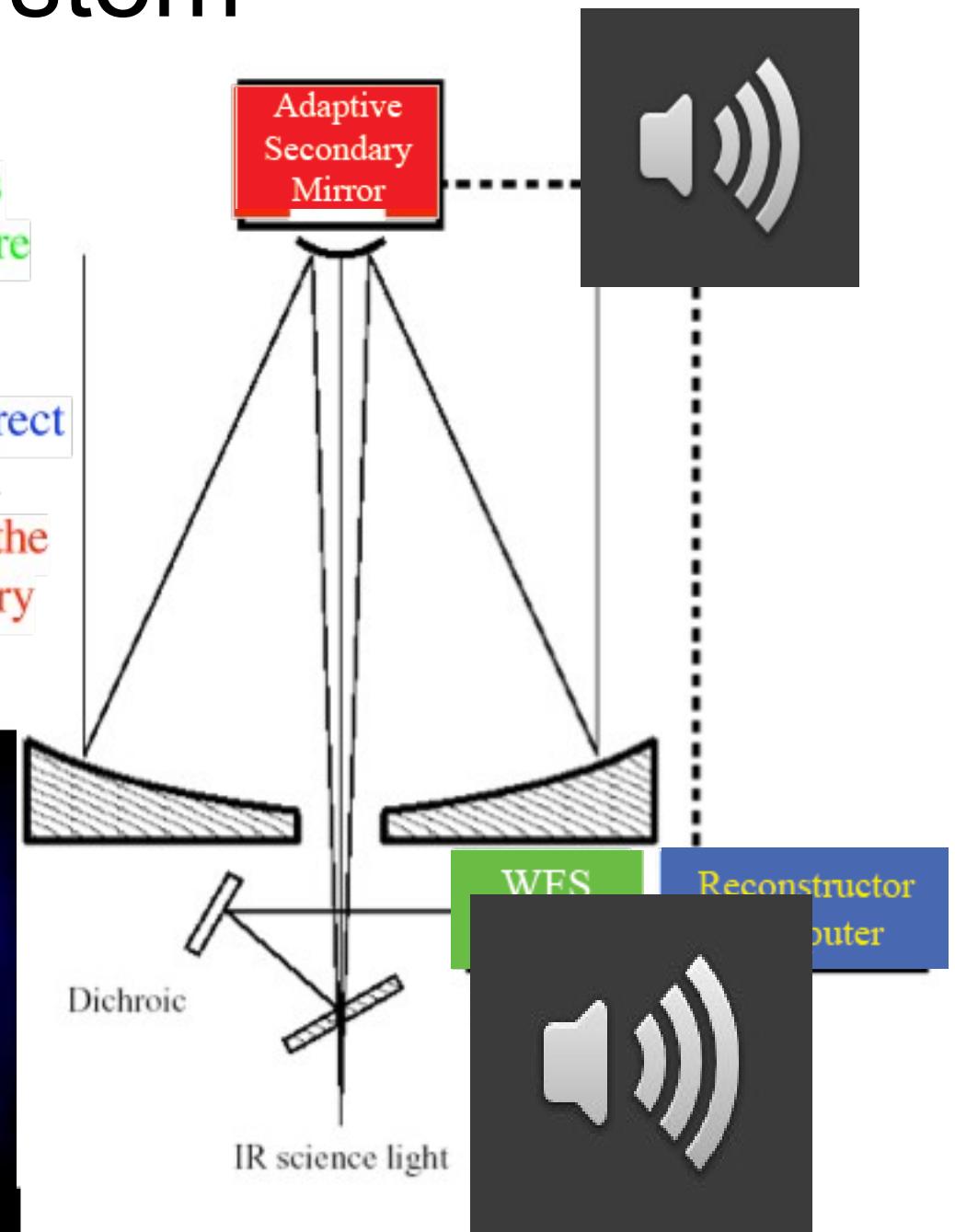
1.

Measure aberrations
due to the atmosphere
with WFS Camera

2.

Calculate secondary
shape needed to correct
measured aberration
Apply this shape to the
deformable secondary

3.



AO On

40% Strehl at H Band



FWHM = 68mas

AO Off

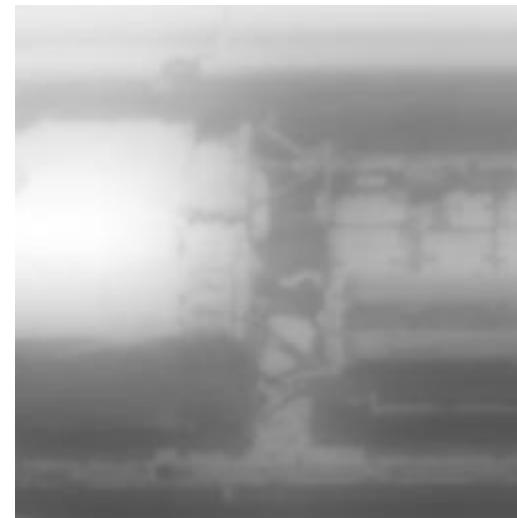
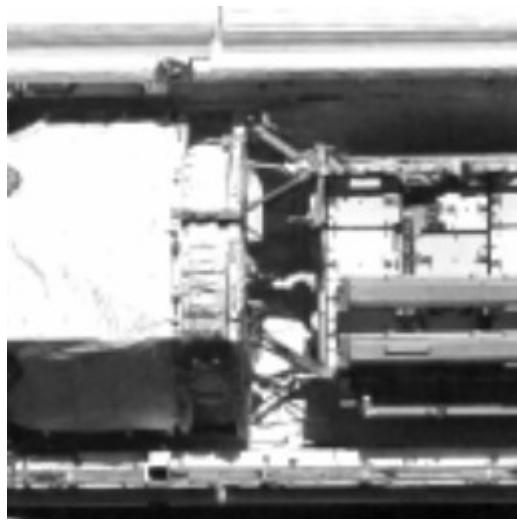
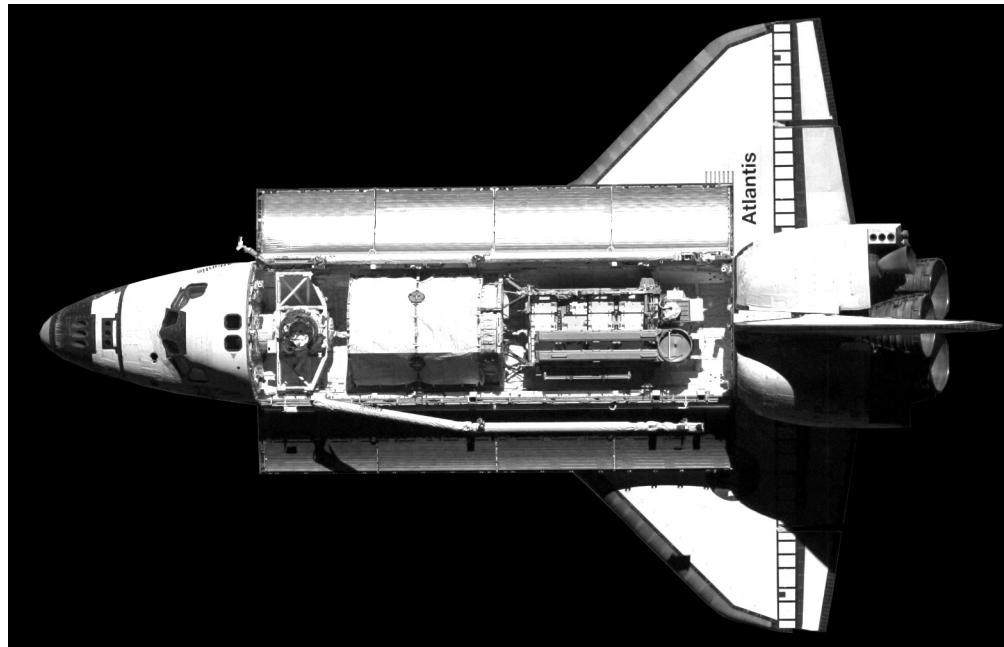
0.87 arcsec seeing

Imaging Sattelites from the ground

ISS 27th Oct 2006

27/10/2006
17:58:17.096
412 km





Atmospheric Layers

