QUICK STUDY

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High-resolution speckle imaging

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Mathematics and technology combine to make a virtue of the graininess imposed on astrophysical images by atmospheric turbulence.

One of the most exciting and challenging pursuits of 21st-century astrophysics is to identify an exoplanet—that is, a planet orbiting an alien sun—on which life may exist. Such a planet is likely to reside in the habitable zone of its sun, meaning that it can harbor liquid water on its surface. Many astrobiologists posit that a life-harboring planet must also be small, rocky, and similar in density to our own. One critical input to any future discovery will be a precise determination of the planet radius, a value that will probably be obtained with the help of high-resolution speckle imaging.

Speckle imaging has been around for a while. It was first conceived by Antoine Labeyrie in 1970 as a way to recover high-resolution features in images limited by atmospheric blurring. Labeyrie's work led to a cottage industry in astronomy through the 1970s and 1980s, as astronomers realized that large-aperture telescopes could produce diffraction-limited images that beat the atmospherically imposed resolution by a factor of 20 or more.

The figure shows how the technique works. In a short time exposure of, say, a star, the turbulence of the atmosphere creates a grainy image, with bright points—speckles—spread over approximately 1 arcsecond in the image plane. In an image of a binary system, the speckle patterns of the two stars overlap; the double image pattern shown in panel a can often be noticed by a trained eye during observations. Normal astronomical imaging involves long exposure times, during which the turbulent cells over the telescope aperture change. The speckles roil and boil on the image plane, overlap and wash out, and yield a smooth image of the star, as shown in panel b.

Labeyrie's realization was that the complicated, short-exposure, speckled image contains high-resolution information in the form of the grains. That information can be extracted via correlations and Fourier analysis of multiple images—thousands or more—to yield a high signal-to-noise ratio. Panel c of the figure shows a typical result.

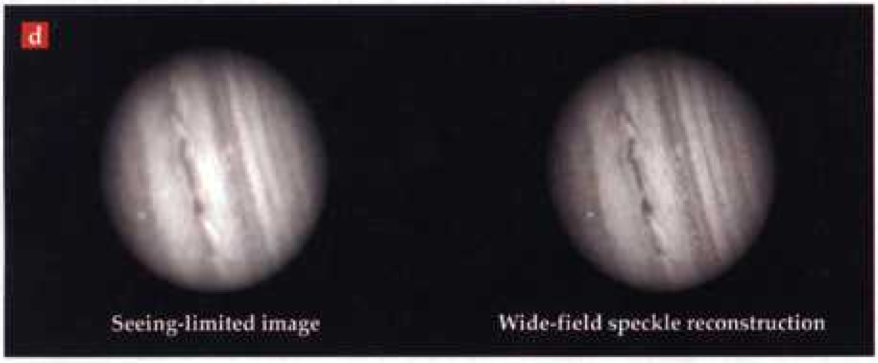
Speckle versus adaptive optics

For 20 years after speckle imaging was conceived, astronomers used the technique in many kinds of studies. But it wasn't a panacea. For the method to work, a detector had to record enough light per frame that meaningful correlation functions could be obtained. It also had to be nimble enough to keep up with the turbulent variations in the atmosphere, meaning that it had to register tens of images per second. Unfortunately, detectors with sufficient readout speed had low quantum efficiency; in less technical language, they did a poor job of converting impinging photons into a measurable electronic signal. As a consequence, even with a then-impressive 4 m telescope, a practical limit for speckle imaging was about 10th magnitude—about 1/100 times as bright as you can see with the unaided eye. That's useful for some kinds of astronomy, but it leaves out a lot of other science.

During the late 1980s and continuing into the 1990s, adaptive optics was developed for large telescopes. It is another method for dealing with atmospheric turbulence and, like speckle imaging, its infancy came with some issues. For example, it was typically only available in the IR, not the visible; its correlations were imperfect; and it added systematic noise. Moreover, it demanded a high observing overhead—a large investment in time for setup and data collection. But because adaptive optics was a way to get high-resolution images onto an astronomy-grade IR detector, adaptive optics systems won the favor of many astronomers for high-resolution work. Poor speckle: Despite its superior resolution for a given aperture, it could not compete in the faintness game.

Things turned around for speckle imaging shortly after the turn of the century, with the appearance of electron-multiplying CCD cameras. Those devices offer the same quantum efficiency as high-grade astronomy CCD cameras, but they are far less noisy even when operating at extremely fast readout speeds. And astronomical speckle patterns could be obtained quickly enough and with sufficient fidelity and sensitivity to image faint stars. More precisely, under good conditions, a state-of-the-art 8–10 m telescope could image stars as faint as 18th magnitude, about 1/200 000 times as bright as can be seen by the unaided eye.

How do modern speckle and adaptive optics imaging compare? Astronomers routinely use speckle imaging at optical wavelengths, whereas most adaptive optics systems are still optimized for IR. Given that diffraction-limited resolution is dependent on wavelength, the difference allows speckle imaging to achieve three- to fourfold better spatial resolution than adaptive optics. Speckle imaging is relatively inexpensive. The state-of-the-art 'Alopeke (Hawaiian for "fox") speckle imager at the Gemini North telescope was built for less than $300 000;



SPECKLE IMAGING IN A NUTSHELL. A 60 ms exposure of a bright binary star system **(a)** shows the characteristic speckling caused by atmospheric turbulence. **(b)** Those speckles become blurred together and thus undetectable in a longer-exposure image. The diffuse image here illustrates so-called seeing-limited resolution. **(c)** As described in the text, mathematical reconstruction based on many speckled images can resolve the two stars that are not separately imaged in panels a and b. The stars here are separated by approximately 0.3 arcseconds; panels a–c are all 1 × 1 arcsec in size. **(d)** Nowadays speckle imaging can be applied over a relatively wide field; these images of Jupiter, taken by the 'Alopeke speckle imager, are 42.5 arcsec across. The reconstructed speckle image does not quite reach diffraction-limited resolution, but it clearly yields higher resolution than the seeing-limited case and better reveals the structure of the cloud bands.

a comparably advanced adaptive optics system for the same telescope would cost in excess of $10 million.

Speckle imaging is a shoot first, ask questions later approach. It demands nearly zero observing overhead because all the analysis is done after the images are obtained. Not that the analysis is easy. Large adaptive optics systems, in contrast, require setup time for proper tuning. The result of that effort, though, is that the recorded images have already been corrected and exhibit high resolution.

Imaging exoplanets

In 2009 NASA launched the *Kepler* satellite, which was designed to determine how frequently Earth-sized planets orbit Sun-like stars. *Kepler* discovered exoplanets by using the transit technique; it measured the light emitted by a star and searched for dips in the light intensity caused when a planet passes in front of the star's surface. The dips are small, proportional to the ratio of the planet area to the star area. For Jupiter-sized planets transiting stars comparable in size to our sun, the intensity drops by about 1%; for Earth-sized bodies, the dip is only 0.01%.

As part of the *Kepler* mission, our research group undertook a detailed imaging study of the host stars believed to harbor alien planets, and we showed that about half the stars hosting exoplanets are in binary star systems. Such binaries, if unresolved, can cause a problem when one attempts to measure the radius of a planet: When a planet passes in front of one of the stars, the measured dip will be shallower than it should be since it is corrupted by light from the unseen companion star. As a result, the deduced planet radius will be too small. And not knowing the planet radius will lead to a poorly constrained or incorrect mean density even if the planet's mass is precisely determined. Because of such an error, a presumed rocky planet could actually be an ice giant.

Speckle imaging is currently helping to validate and characterize the transiting exoplanets discovered during NASA's *K2* (the successor to *Kepler*) and *Transiting Exoplanet Survey Satellite* missions. New speckle instruments on national observatory telescopes are now available to the scientific community for studies of binary stars, star-forming regions in galaxies, globular clusters, solar-system objects, and more. One exciting advance that our group just achieved is to apply speckle-imaging techniques over a relatively wide field of view, as shown in panel d of the figure. Although at an early stage, wide-field speckle imaging can already resolve features nearly as well as current IR-based adaptive optics systems, and it achieves that enhanced resolution at far less cost in time and money.

Additional resources

▶ E. P. Horch et al., "Most sub-arcsecond companions of *Kepler* exoplanet candidate host stars are gravitationally bound," *Astrophys. J.* **795**, 60 (2014).

▶ S. B. Howell et al., "Speckle imaging excludes low-mass companions orbiting the exoplanet host star TRAPPIST-1," *Astrophys. J. Lett.* **829**, L2 (2016).

▶ E. Furlan, S. B. Howell, "The densities of planets in multiple stellar systems," *Astron. J.* **154**, 66 (2017).

▶ R. Matson et al., "Stellar companions of exoplanet host stars in *K2*," *Astron. J.* **156**, 31 (2018).

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