Direct Detection of Exoplanets

An optical technique that uses the wave nature of light could reveal planets outside our Solar System more accurately.

Marija Strojnik

The first time astrophysicists detected a planet outside of our Solar System around a Sunlike star was in 1995, and since then, more than 5,000 extrasolar planets (or exoplanets) have been identified. Despite that impressive number, detecting exoplanets is an incredibly difficult task. For an exoplanet the size of Jupiter, the planet is about a million times fainter and a hundred times smaller than the star it orbits. There is currently no optical instrument on Earth or in space that can separate these two objects as individual entities. Instead, the existence of such an exoplanet can be inferred from various data, but no Jupiter-equivalent exoplanet has yet been directly detected. We can assess its distance from its star and its temperature, but very little other information.

So far, exoplanets that are giant or that orbit very close to their stars (or both) have been the most readily detected. To systematically find exoplanets that more resemble Earth in size, temperature, and distance from their star—thus increasing their likelihood of being habitable—will require innovative approaches. Research that I have conducted from theoretical calculations in the 1990s to a proof-of-concept experiment in the past few years considers how to use the wave nature of light as a tool for direct detection of exoplanets, potentially with greater accuracy than current methods permit. Although this technique could take several decades to be proven and implemented, it has the advantage that the signal used can be present only when an exoplanet exists, reducing the possibility that anomalies will affect the system.

How to Search for an Exoplanet

Exoplanets cannot be detected visually, so astrophysicists began to look for other measurable quantities that can be detected in the physical characteristics of a star and that create an anomaly that would likely not exist if the star did not have orbiting planets. All the current techniques of exoplanet detection have been adapted from radiometric measurements, in which a temporal dependency is introduced because the planet orbits its star and thus provokes a measurable change in some of the star's parameters.

Arguably, the most productive planet detection technique has been what's called the *transit method*. A dim, small object orbiting a bright, large object will decrease the amount of light that an observer receives from the bright object only while the dim object travels in front of it. This dip in the detected power is then related to the planetary orbit and other parameters of celestial mechanics. The downside of this technique is that it is using a small, indirect signal, which could be confused with some other anomalous signal from the star instead of coming from a planet.

Another interesting technique of planet detection is the *radial velocity technique*. In a planetary system, we can see only the star. Half of the local year—that is, the time that the planet travels around the star once—the planet is traveling toward an observer, and the other half of the local year it is moving away from an observer. The relative speeds of the planet are highest and lowest when the planet is at its largest distance from the star, as seen by the observer. This relative change in speed means that when the planet moves away from the observer, the spectrum of the electromagnetic radiation it emits is shifted toward longer wavelengths. Conversely, when the planet travels toward the observer, its spectrum shifts toward shorter wavelengths. The time between the high and low peaks in the planet's spectrum tells us the length of the local half-year, and the amplitudes of the peaks can be used to deduce the planet's mass. However, the temporal separation between the two measurements, of half of the local year, makes such radiometric measurements very demanding. In half an Earth year, the precision of the detection instrument could be improved by more than the power of the signal from an exoplanet. Thus, this method has mostly been used to find planets that orbit close to their stars and therefore have short local years.

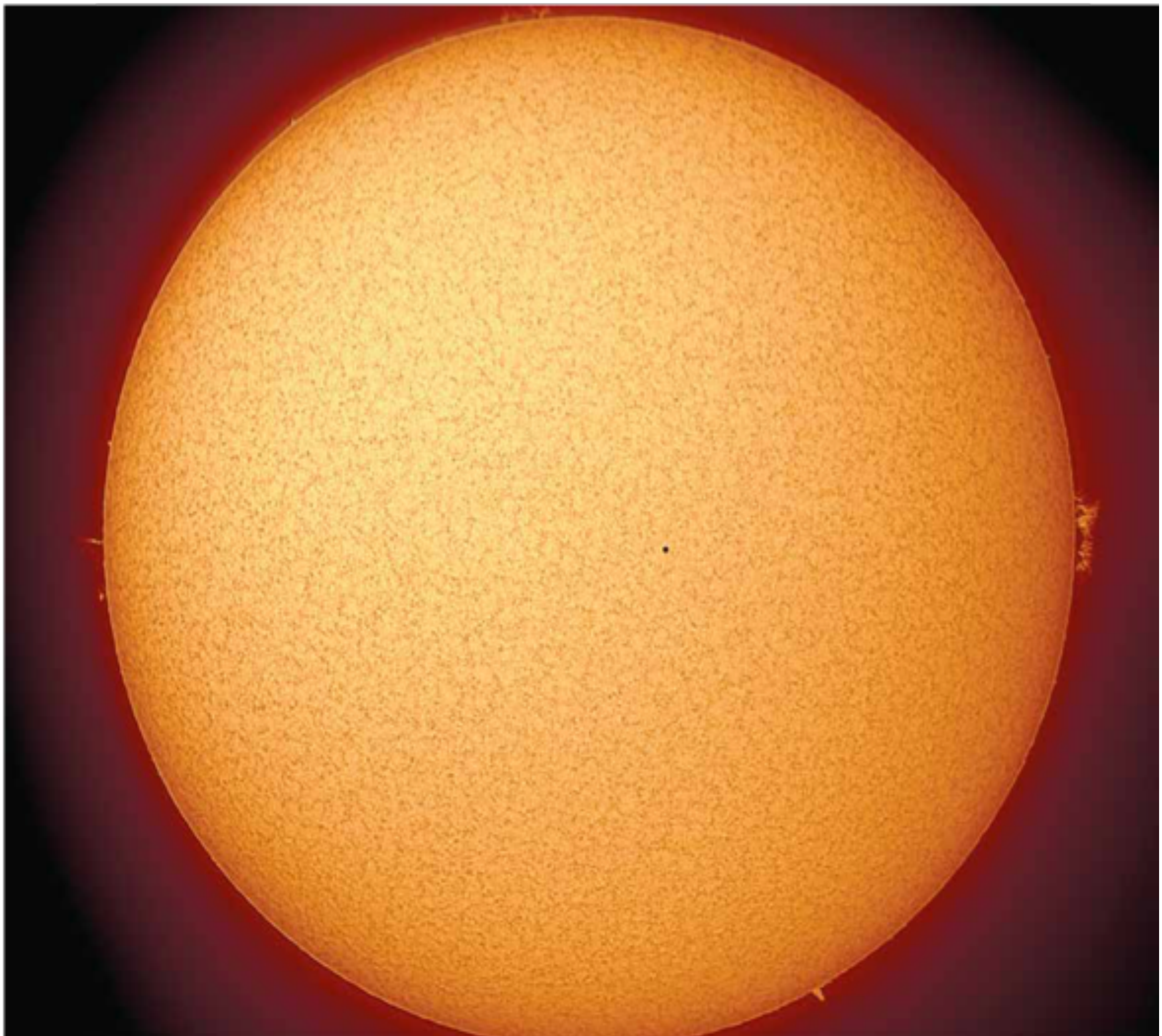
Astrometry is a technique that uses interferometry to measure the distance to a star with unknown coordinates with respect to a known star. *Interferometry* is similar to throwing two rocks into a calm pool of water, creating two sets of concentric circular waves until the waves meet and the pattern breaks. In astrometry, optical radiation is collected from a reference star and the unknown star and then interfered. The resulting pattern is a set of parallel straight lines, called *fringes*, directed

QUICK TAKE

Thousands of exoplanets have been identified using several different methods, which mostly use the amount of light, radial velocity, or "wobble" of those planetary systems.

All of these methods currently have drawbacks, including a large time separation between measurements, which introduces the potential for errors.

A method adapted from optical testing uses the wave nature of light to allow measurements to be made in immediate succession, potentially increasing accuracy.



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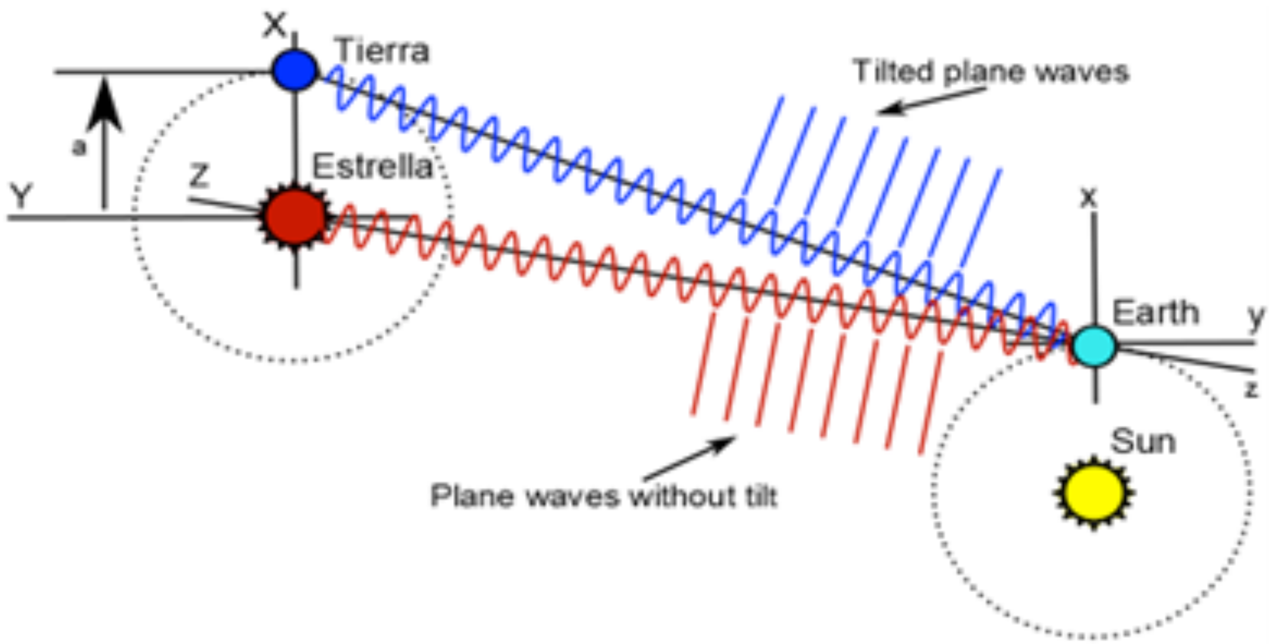
In 2019, Mercury *transited* the Sun, meaning it crossed in front of the star as viewed from Earth. In this image, the tiny planet is a dot that can be seen just below right of center of the Sun. Transits are used to identify extrasolar planets around their stars, but the measurements are indirect. An optical method using the wave nature of light could provide a means of direct detection.

perpendicularly to the line connecting the stars. The distance between fringes is inversely proportional to the star separation, meaning the larger the separation, the smaller the distance between two neighboring fringes, and this distance can be used to calculate the separation between these two celestial objects.

When the unknown star has a planet, the visible star behaves as a variable star, rotating around the common center of mass of the star and planet. The detected interference pattern changes in time and goes through a complete cycle during a local year, when the planet completes one orbit about its star. When the invisible planet is between both stars, the center of mass of the planetary system moves closer to the reference star, and the interference pattern presents fringes that are slightly more separated. When the planet is on the same line as both stars, but distant from the reference star, the center of mass of the planetary system moves away from the reference star, and the interference pattern presents fringes that are slightly less separated. This change in fringe separation over time could be considered a *derivative*, a technique that is used to measure a small signal buried under a large, constant level of noise. However, this technique is also hampered by requiring two precision measurements separated by a large time interval, creating room for error. Nonetheless, the European Space Agency's Gaia mission has recently started detecting exoplanets using this technique.



Light waves that travel from other stars and their exoplanets originally start out as spherical waves, but after they travel long distances to reach Earth, these light signals will become plane waves. The light wavefronts originating from the orbiting exoplanet will be inclined in comparison with its star, because the planet is located at an off-axis position. This different positioning of the two wavefronts can be used to create an interference pattern that shows the existence of the exoplanet.

Finally, there is the imaging technique called *coronagraphy*, which was discovered about 100 years ago when scientists were trying to understand the Sun and its corona. The bright Sun tends to overwhelm its corona, so this technique uses a black mask to occult the Sun while its corona alone is observed. Similarly, in the search for exoplanets, an occulting aperture is used to block the star's radiation while its planet is observed. This technique has been studied for exoplanet detection only in the past few years, and it is best for widely separated, young, high-mass planets, but there are upcoming programs that plan to utilize this technique.

A New Search Technique

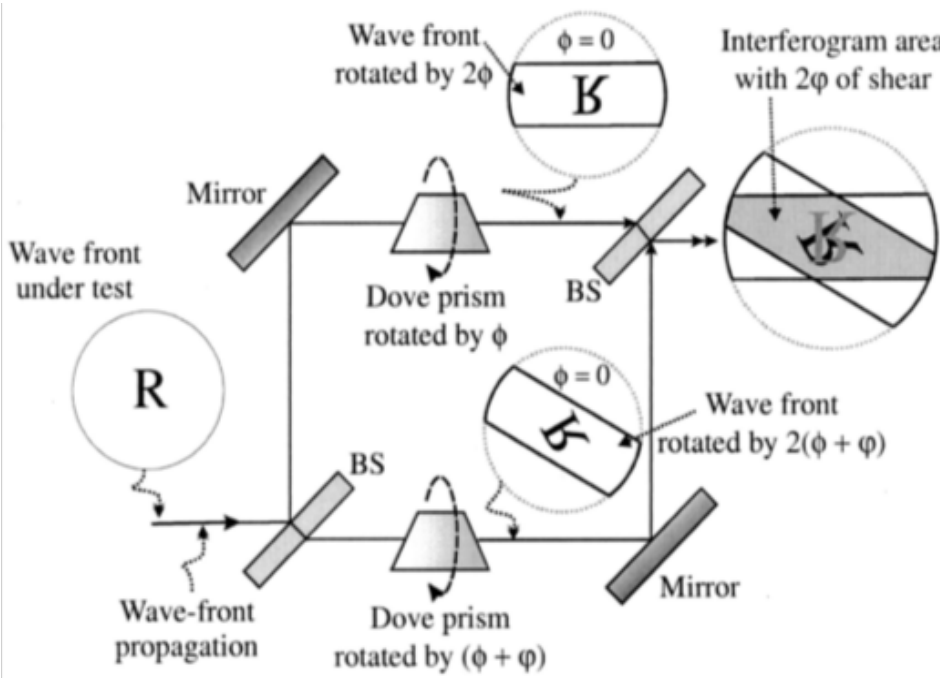
My planet search story began at the Jet Propulsion Laboratory (JPL), managed for NASA by the California Institute of Technology. JPL is tasked with robotic spacecraft exploration of the Solar System. Although most of the instruments in their robotic exploration are controlled from Earth, the robot's optical navigation uses an onboard autonomous computer system that incorporates a library of stars and an algorithm. In 1992, I demonstrated this system's successful performance at an observatory as a technology development project, in support of the Cassini mission to Saturn, which launched in 1997 and ended in 2017.

As JPL analyzed the robotic images from the objects in our Solar System, the logical next step was for their scientists to assess the possibility of searching for planets outside our Solar System. That problem was much more difficult than examining a planet next door, and it included several almost-impossible-to-solve technological problems, a truly delicious puzzle for scientists: resolution, distance, dynamic range, signal-to-noise ratio, and scattering, to name just a few. I became involved in this work at JPL as an optical scientist with a specialization in infrared and instrumentation. My expertise gave me a different perspective from planetary scientists. I began working on the theoretical foundations of an optically based technique in the 1990s, which was developed into a proof-of-concept model in 2019.

When analyzing successful and promising planet detection techniques, we learned that several of them take an imperfect derivative of a signal: Long time separations are involved, allowing for the possibility that systematic errors, ghost images, and degradation because of aging could be introduced. The other useful lesson from astrometry was that we really do not need to obtain the whole image of the searched object, because two objects can create a single signal. The presence of the second object can be established simply by detecting an interferometric signal. It occurred to me that a technique used in testing optical surfaces could be adapted to similarly use two objects to create one signal, but without the time delay between signals that allowed for the introduction of errors.

Outside of its use in astrometry, interferometry is also a common technique used to test the quality of optical surfaces in telescopes: By interfering light beams that travel to the test surface and to a high-quality reference surface, optical engineers obtain intensity distributions that they relate to the quality of the surface under test. But within the past 50 years, we have seen a rapid development of the optics industry, so successful that we have run out of suitable, easily fabricated reference surfaces to use in tests. The solution has been to use *self-referencing* for testing. If the test surface is measured, then displaced slightly along one axis, then remeasured, the two measurements produce a derivative. Using mathematical integration, we can recover the surface shape and determine deviations from the shape's required value. This operation of displacing a surface with respect to itself is called *shearing*.

Besides displacing a surface horizontally, one can also rotate a surface. Most traditional optical systems, and therefore their constitutive compo-



A key element in a rotational shearing interferometer is a Dove prism, an optical device that can be rotated to change the orientation of the wavefront that passes through it. A test wavefront, here the letter R, is split into two beams that pass through different Dove prisms. The top Dove prism rotates the R by 180 degrees. The bottom Dove prism can be rotated by incremental angles to change the wavefront. When the two beams are recombined, they create an interference pattern, or interferogram, that can be used for optical detection.

nents, exhibit rotational symmetry around the optical axis, which in this case would be the axis of symmetry.

If we wanted to test whether a surface is actually rotationally symmetric, we could optically couple it to a *rotationally shearing interferometer* (RSI). We start out with what's called a *Mach–Zehnder interferometric configuration*, in which each beam travels along each path only once. We transform it into an RSI by inserting what's called a *Dove prism* into each interferometer arm; one of the Dove prisms is rotated so that it also rotates the wavefront, whereas the other wavefront passes through unaffected (*see figure above*). When the beams are combined, the wavefronts are superimposed and subtracted, generating an interference pattern that contains the information about how similar the rotated surface is to the original surface. We increment the orientation angle of the Dove prism by a few degrees in a series of measurements until the rotation angle of 360 degrees is achieved. At that time, the surface is compared again to the original surface.

Let's consider a surface that is perfectly rotationally symmetric, except for a bump a few degrees to the right just below center—as was the case for an image of the Sun on November 11, 2019, when Mercury *transited* the Sun, meaning it traveled in front of the Sun as viewed from Earth (*as shown on page 297*). If this surface is rotationally sheared and measured, all the subtractions between successive surface positions for different orientation angles would result in a signal at the bump location. The bump would trace a radial anomaly. Therefore, my group at the Optical Research Center in León, Mexico, had the idea of using an RSI to look for anomalies with stars that indicate exoplanets, rather than surface aberrations in optical surfaces.

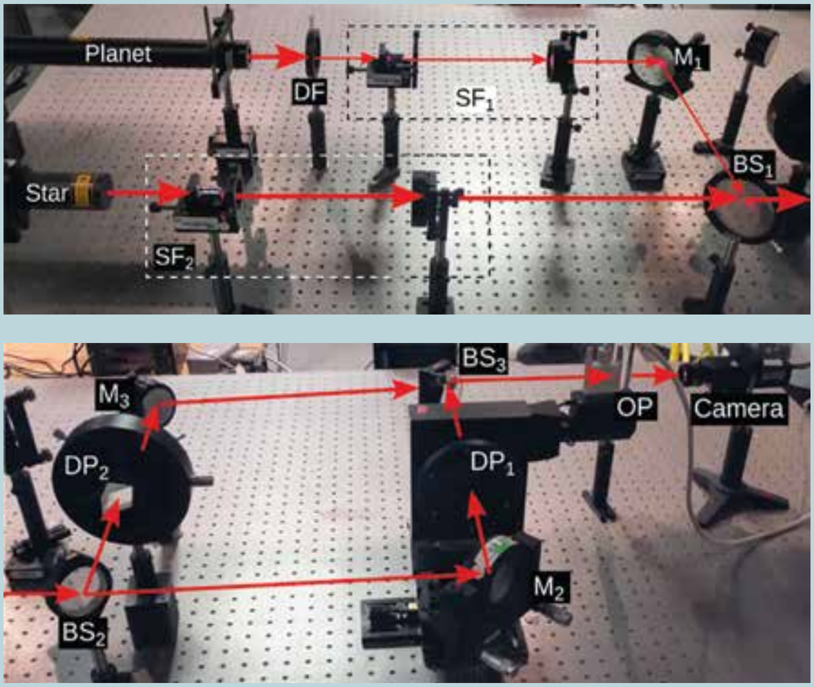
The instrument will focus on the star because its overwhelming brightness is all we can see. But if there is a planet, perhaps in orbit at the distance of Jupiter, it will introduce asymmetry into the measurements. We can use the wave nature of light to detect the planet. The spherical waves that originate at the star and its planet separately, after traveling the long distance to the Earth, become plane waves. But the wavefronts originating from the planet will be inclined, because the planet is located at an off-axis position (*see figure on page 298*). The star's wavefront also includes some inclination angles, but they are all nearly zero. A filter that eliminates small-angle plane wave spectra will leave only the planet information.

If there is a planet, it will introduce asymmetry into the optical measurements.

A lone star is a perfect example of a rotationally symmetric optical system. Outside the Earth's atmosphere, a star looks like a flat white circle, because of the isotropic nature of its radiative emissions. If you rotate an image of the star alone by a few degrees and subtract its emission characteristics from those of the original, you would end up with zero.

The situation is appreciably different when we are dealing with detecting a distant star and its planet with an RSI located on Earth or in its orbit.

To implement this filtering with rotational shearing interferometry, we subtract one complete wavefront that is incident on the interferometer from the same wavefront that has been mechanically rotated using a Dove



A laser setup tests the concept of detecting a planet around a star with rotational shearing interferometry. The beam from the "star" is on axis with the system, whereas a beam from a "planet" is offset (by mirror M_1) as it would be in orbit. Laser beam paths are shown by the red arrows. Laser beams first go through a set of filters (shown by DF, SF_1, and SF_2) and beam splitters (BS_1 and BS_2), so the combined light of star and planet goes through two Dove prisms (DP_1 and DP_2). The Dove prism at DP_1 is rotated, introducing a wavefront shear in the signal. After the beams are recombined (at BS_3) and the output (OP) is imaged by the camera, the derivative shows interference fringes that indicate the planet. (Images courtesy of the author.)

prism. This action results in a destructive interference for all positions on the aperture except where the planet is located. There, we detect an inclined wavefront, which in the RSI manifests itself as straight fringes, just as in astrometry. But the fringes are recorded during a single measurement, taking less than a few hours.

Our technique of exoplanet detection therefore addresses the challenges of eliminating the elapsed time between consecutive measurements, avoiding systematic errors, and eliminating the validation of results using statistical means. It takes a derivative with respect to angle corresponding to the orientation of the planet with its star, so when there is no planet, there will be no fringes.

Putting the Technique to Work

We know that two-aperture interferometry works well, because it has been successfully implemented in astrometry to measure star positions. With the RSI, we have a faint planet instead of the second star. Fringes are visible only if the planet is within the field of view of the instrument. But both our simulation studies as well as our theoretical analysis indicate that the density of fringes (the number of fringes per unit distance) and their orientation change with the change in the Dove prism orientation. Thus, the planet's presence may be further confirmed by changing the Dove prism orientation angle, and the existence of a fringe pattern may be directly and causally related to the presence of a planet.

In 2019, we built and tested the first concept demonstration for the RSI. A simulated planetary system made from two lasers is coupled to an RSI (*see the figure above*). The star laser beam and its beam-conditioning components are aligned to the RSI axis. The planet laser beam is placed at a slight angle with respect to the star laser beam. The planet laser beam is coupled to the star laser beam with a cube beam combiner.

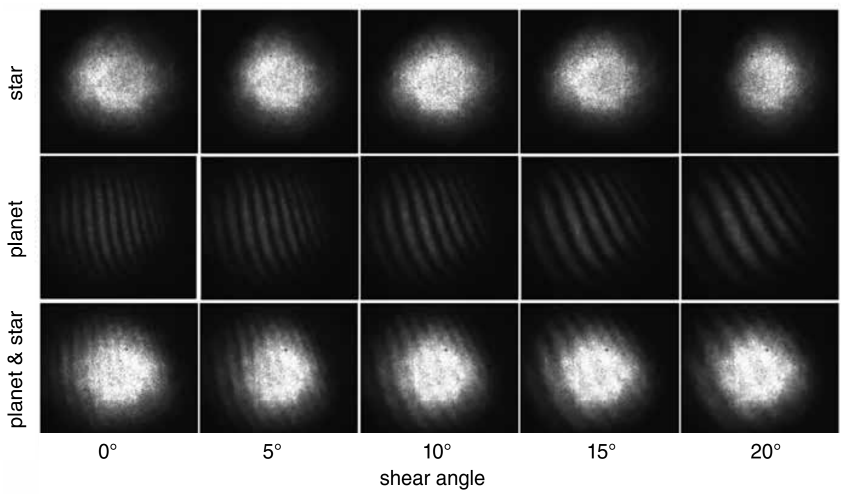
A cube beam splitter divides the combined incident wavefront into two beams and sends them into the two interferometer arms. A Dove prism in each arm transforms the interferometer into an RSI. A rotated Dove prism rotates the wavefront in one interferometer arm (the horizontal one after the beam splitter) with respect to the beam in the other arm (the vertical one after the beam splitter). An identical, stationary Dove prism in the reference arm compensates for the changes in the optical path. The beams traveling through two arms of the RSI overlap once again at the second beam combiner, and the interferograms are captured by a camera.

The interferograms obtained with the experimental setup when the angle of orientation of the Dove prism increases from 0 to 20 degrees are displayed in the figure above. We considered three cases: only the star laser is on, only the planet laser is on, and the complete planetary system simulator is on.

In the first row, the interference patterns remain unchanged when the angle of orientation of the Dove prism increases from 0 to 20 degrees for a single point source (star laser) on the optical axis. This series of interferograms confirms that the RSI is insensitive to a solo star located on the optical axis. A bright field is detected for all angles of the orientation of the Dove prism. No fringe pattern rotation is observed when the incident star wavefront possesses rotational symmetry. This is the case for a star without a planetary companion when the instrument is aligned with the star center.

In the second row, the interference patterns change when the angle of orientation of the Dove prism increases from 0 to 20 degrees for a single point source (planet laser) placed at an angle with respect to the optical axis. The practically straight interference fringes decrease in density and increase in the inclination angle when the shear angle is increased. This is one of the characteristics of the RSI when measuring the tilted wavefronts. This experimental data confirm that an off-axis source may be detected in an RSI by generating straight fringes.

The existence of a fringe pattern may be directly related to the presence of a planet.



Results of testing a proof-of-concept system for radial shearing interferometry show the different outcomes if the simulation involves a light signal from only a star, only a planet, or a planet with a star. The interference fringes only appear if a planet is present, and confirm that the fringe density and inclination angle change with the shear angle. (Image courtesy of the author.)

Furthermore, the fact that the fringes arise from an off-axis source, rather than because of an artifact, may be confirmed by changing the shear angle.

Likewise, in the third row, the interference patterns change when the angle of orientation of the Dove prism increases from 0 to 20 degrees for a complete planetary system (a bright point source on-axis and a weaker point source off-axis). These interferograms are similar to the planet-only interferograms, except that the star incidence provides the background in the central portion of the interferograms. This is a consequence of the Gaussian shape of the laser incidence. Filtering the constant background or mirroring bright and dark pixels would eliminate these effects.

Our experimental data confirm that a dim off-axis source next to a bright source on-axis may be detected in an RSI. The dim source generates faint fringes on top of the bright star incidence, as predicted by theory. The theoretically predicted change of the fringe inclination angle with the shear angle is also confirmed, making the RSI as a planet detection technique fault-tolerant to a spurious signal. The theoretically predicted change in the fringe density is also confirmed in the experiment.

The next step is for our proof-of-concept experiment is to build engineering models, have a demonstration in an observatory environment, and further increase design optimization. Then, NASA or some other space agency may decide to adopt it. At that time, it will take at least a decade to incorporate the RSI planet detection instrument into a mission. Until we reach those later demonstration stages, we won't be able to prove for certain that an RSI can discriminate better than current instruments between planets and the other miscellaneous information noise. But so far, the results have been promising. I believe that the time has come for us to start building instruments that can speed the measurements of exoplanets using signals that intrinsically are present (or absent) if the planet is there (or not). No other planet detection technique has such strong fault-tolerance and causality built into its detection scheme.

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Marija Strojnik is a distinguished professor at the Optical Research Center in León, Mexico. Email: mariasigmaxi@gmail.com