Light + Light = Darkness

Searching for exoplanets

Arjan Mieremet, a doctorate student in the Optics section at Applied Physics, wants to extinguish stellar light in order to see the planets around it. The idea originated over twenty years ago, but so far nobody has managed to construct the necessary optical equipment. Mieremet tried, and soon ran into problems. This was not such a bad thing, since it resulted in his discovering a major theoretical improvement. If all goes well, astronomers in 2015 will be able to catch stellar light.
using six space telescopes, and combine it to form... nothing! Or rather, nothing and a bit, and the bit will hopefully turn out to be the light reflected by an Earth-like planet. Molecular lines in the light’s spectrum may even point to the presence of extraterrestrial life. These certainly are interesting times.

In most cases, astronomers aim to enhance the weak light from the stars as much as possible. One option is to build a telescope with a very large mirror. A larger mirror will catch a larger part of the wave front, and so collect more photons. Gravity restricts the size of earthbound mirrors to about eight metres in diameter. To catch more photons, the light collected by a number of different telescopes can be combined. This process, which simulates a much larger mirror, is called aperture synthesis. For this, light of the different telescopes must be exactly in phase, so only the parts of the same wave front will be combined. Since the distance between the star and each of the telescopes varies, the difference in path length must be corrected by using delay lines to slow down each of the wave fronts until the last wave front has been collected. In a delay line, the light has to travel an extra path length. The end result is that the wave fronts of the various telescopes will be exactly in phase at the point at which they are combined, and will amplify each other through a process known as constructive interference.

Lord Kelvin

Sometimes the light is simply too bright to permit accurate observation. During the day, for example, we cannot see the stars because the Sun outshines them. To us, the Sun appears 10,000 million times as bright as Sirius, the brightest star. The only time we can see the stars in daytime is during a total solar eclipse. For the same reason, we cannot see any stars near the Moon in the sky, for the (full) Moon is 6000 times as bright as Sirius. Likewise, if we were to look at our own solar system from a great distance, we would only see the Sun and none of the planets. In the visible part of the spectrum the brightness of the Sun is about 1,000,000,000 times that of the Earth, which like any other planet does not itself produce light, but simply reflects the light of the Sun. On the other hand, in the infrared range, the Sun is «only» one million times brighter than its planets.

Over a century ago, William Thomson (better known as Lord Kelvin) stated that we would never be able to see the other side of the Moon. In 1959 the unmanned Russian spacecraft, Luna 3 photographed the back of the Moon.

Most astronomers do not doubt the existence of planets orbiting other stars. What they do have their doubts about is our ability to observe such planets. In 1995, Michel Mayor and Didier Queloz discovered a large, gaseous planet in an orbit around the star known as 51 Peg (in the constellation of Pegasus). Since that time, over 100 of these «exoplanets» have been found. Finding these planets is an indirect process, as an exoplanet is outshone by its «host», the star it orbits. Nevertheless, the planet gives away its presence through

---

We expect that many stars have one or more planets, known as exoplanets. The search for these planets is in full swing, and already more than 100 examples have been found by means of indirect methods. These methods are based on the gravitational effects the planet has on the star. This explains why all the exoplanets found so far are comparable in mass to Jupiter. The challenge is to detect the smaller, more Earth-like planets. This will require other, direct techniques since these planets have too little mass to enable them to be detected using gravitation techniques. However, direct detection is a problem since stars outshine their planets a million times or more.

---

The Very Large Telescope (VLT) at the summit of mount Paranal in Chile comprises an array of four telescopes. Combining the light collected by each telescope with the light of the other telescopes enables observations at a resolution that is many times larger than that of a single telescope. The process is called aperture synthesis. The rail structures on the ground will carry four auxiliary telescopes, with smaller mirrors, which will help increase the resolution even further.
its gravitational interaction with the star. The star exerts a gravitational pull on the planet, and vice versa. As a result, the common centre of gravity is not exactly in the middle of the star, but slightly off-centre towards the planet. Both the star and the planet orbit around this point. The planet follows an elliptical path that coincides almost perfectly with its orbit around the centre of the star. The star, since it is much heavier, follows a path that is almost entirely within the star’s diameter, causing the star to wobble slightly. The star’s motion can be observed in two different ways. If the planetary orbit coincides with the plane of the sky, the star appears to move periodically. High-resolution astrometry (the science of measuring star positions, usually relative to each other) can then be used to deduce the presence of a planet. In the other case, when the planet orbits perpendicular to the plane of the sky, (so the planet passes in front of and behind the star from our point of view), the star executes a periodical motion along the line of sight. i.e. it appears to move towards us and away from us. Accurate measurements of the radial velocity can then show a periodical Doppler shift of the stellar light spectral lines, demonstrating the presence of a planet. The observations also give us the planet’s orbital period, its distance from the star, and an estimate of its minimum mass. Jupiter, which is the heaviest planet in our solar system, has a similar effect on the Sun. Astronomers on a nearby exoplanet will see our Sun wobble with a 12-year period, which is the orbital period of Jupiter.

Earth-like planets
All the exoplanets discovered so far have at least the mass of Jupiter. This is an effect of selection. Earth-like planets cannot be detected using indirect methods as their small mass results in gravitational effects that are too small to be distinguished from other effects. The Earth’s mass is three hundred times smaller than that of Jupiter, and the effect of the Earth on the Sun (using the radial velocity method) is only 10 centimetres per second. On the other hand, convection causes the surface of the Sun to move at a rate of several metres per second. Direct observation methods are needed to detect Earth-like planets. Given the fact that a star shines 1,000 million times as bright as a planet, the chances of discovering an exoplanet like the Earth appear to be slim, or would that be as short-sighted as Lord Kelvin’s tenet proved to be?

In 1979 Ronald Bracewell suggested the idea of «nulling interferometry» as a means of observing exoplanets directly. Two telescopes, pointed at the same star, both receive the light of the star plus the (much weaker) light of any planet orbiting around it. Bracewell proposed that the light of the star, as observed by the two telescopes, be made to interfere destructively. A phase shift of \( p \) radians (180°) in one beam would cause the maximums of the wave front of one to perfectly coincide with the minimums of the other beam, the net result being «zero», i.e. darkness. The difference in optical path length causes any light from a slightly different direction (e.g. right next to the star) to arrive in the telescopes with a slightly different phase shift,
which is sufficient to prevent it from being cancelled out. Depending on the direction, this light could even be made to interfere constructively, resulting in amplification. This method could be used to make a planet visible.

Spectral lines
The discovery of the first exoplanet rekindled interest in Bracewell’s concept. Now that it has been demonstrated that planets do indeed orbit around other stars, direct observation of Earth-like planets is the next goal. The light of a planet also gives us information about the composition of any atmosphere that planets may have. If the light contains the spectral lines of water, oxygen, methane, and carbon dioxide, this might indicate the presence of life on the planet.

Bracewell’s original idea suffers from a number of limitations that hinder the direct observation of planets. The most prominent problem is the limited width of the minimum that results from the destructive interference. Only the light originating from the centre of the star will be fully extinguished, but the light from the edge of the star will not. The residual light still is much brighter than any planet, so the planet will therefore remain invisible. One remedy for this problem is to add a third telescope. The interference pattern of three telescopes has a broader minimum range, so the light from the edges of the star will also be sufficiently cancelled out. An even better proposition is to use four or six telescopes.

‘The principle of nulling interferometry looks very nice on paper, but in a schematic diagram the achromatic phase shifter is simply shown as a rectangle marked «p»’, Joseph Braat, Professor of Optics and Arjan Mieremet’s supervisor, says. ‘About six years ago, I started to think about serious ways of actually constructing it.’

Some years later, Mieremet was awarded his doctorate for the assignment of building a real achromatic phase shifter – the rectangle marked «p».

Creating a phase shift of p radians requires an optical system that delays a light wave long enough to make it lag half a wavelength behind the wave it has to interfere with. The problem is that «half a wavelength» is a different value for any given colour. To create a phase difference of p radians (halve a wave length), red light (l of 700 nm) must travel an extra length of 350 nm, whereas for blue light (l = 480 nm) this is only 240 nm. Therefore, a device know as an achromatic phase shifter has to be constructed, in other words a piece of optics that will shift the wavelength of any colour the same phase range. Braat and Mieremet experimented with so-called dispersive phase shifters. Light travels faster through a vacuum (or air) than through glass. The refractive index of glass is a function of the wavelength (which results in the well-known effect of dispersion), and represents the ratio of these velocities. A person wearing spectacles therefore sees everything a fraction later than people without them. It is not something to worry about, since the difference in time is only a few billionths of a second per millimetre of glass.
can delay a light wave, and so create the required phase difference. However, the problem is that the phase shift must be an exact fraction of the wavelength for every wavelength (i.e. colour). Unfortunately, we do not know of any material that gives exactly the same phase shift for each wavelength. In most cases, a combination of glass, such as BK7 and F2, is used.

Glass sheets
Arjan Mieremet first attempted to build a phase shifter that would «null» properly in the 400 to 1000 nanometre range (part of which is in the visible part of the spectrum). He was not out to achieve an attenuation factor of one million, but a few thousand times had to be on the cards.

Mieremet: ‘We still use visible light for our current experiments. The important thing is to get the principle right before introducing new problems of working with infrared light. Optics for infrared use are much more expensive than those for visible light, and the detection of infrared radiation is highly sensitive to thermal effects.’

Calculations showed that a phase shifter consisting of two different materials was able to achieve an attenuation factor of 3000, and that a combination of three different materials could be used to achieve a factor of 70,000. A phase difference of a half a wavelength could be achieved with sheets of glass only a few micrometres thick. Since this would be impractical, each of the two beams of light was passed through a set of glass sheets whose thicknesses differed by a few micrometres, which has the same effect. In the test set-up, the light of a single source is split into two beams, each of which passes through two sheets of glass and a delay line. The glass sheets and the delay line ensure that the two beams differ half a wavelength in length. The two beams of light then converge in a CCD camera that records the interference pattern.

Unfortunately, Mieremet was unable to achieve the predicted theoretical attenuation.

‘We clearly observed an attenuation, but we were unable to get the right level. The initial idea was to use measurements to achieve the optimum settings for the phase shifters. By changing the orientation of the glass sheets, the optical path length is changed. As the angle at which the light strikes the surface of the glass is increased, so is its path length through the glass. The problem is that it is impossible to manufacture a test set-up with submicrometre precision, so interactive adjustment is needed to obtain the desired degree of accuracy. Sadly, the test results were difficult to match with adjustments to the test set-up.’

Although the experiments demonstrated that the principle of nulling interferometry works, the theoretical attenuation value could not be obtained. So Mieremet decided to take a much closer look at the nulling principle, and to redevelop the theory from first principles.

Mieremet: ‘I discovered that the physical requirements for the phase shifter were in fact absurd. To obtain attenuation factors of a million times, it was assumed that the accuracy of a phase shift of p radians had to be
better than two millirad, regardless of the number of telescopes being used. A millirad is equal to only one six-thousandth of a wavelength. Compare this with the surface accuracy of a very good mirror, which is one twentieth of a wavelength. In the existing theory of nulling interferometry, the requirement for an accuracy of two millirad is maintained for systems using two telescopes. I discovered that, by combining not only phase differences of π radians, but also integer multiples of π, such as 2π, 3π, etc., the required accuracy need not be so strict. What happens is that the errors in the phase differences become correlated and cancel each other to a certain degree. The result is that an accuracy of, say, 50 millirad is sufficient when the light from three telescopes is combined. The more telescopes you add, the larger the error is allowed to be. This certainly makes life a whole lot simpler.

Experimental set-up
In the basement of the Applied Physics building, Mieremet has built a new experimental set-up in cooperation with tno/tpd, the Organisation for Applied Physics. He currently uses only delay lines, without any dispersive elements, to experimentally verify the principle of nulling interferometry with unequal phase differences for three telescopes.

‘There are three separate parts,’ Mieremet explains about the set-up, ‘the part that simulates a star, the part that simulates the telescopes, and the part that measures the combined intensity. In order to obtain a point source, the light from a bright lamp is focused by two lenses onto a pinhole (a hole with a diameter of three micrometres). The lens behind the hole turns the light passing through the pinhole into a parallel beam. The parallel beam is aimed at another hole with a diameter of one centimetre, resulting in a well-defined beam of white light with a flat wave front to simulate a star at large distance.

I then use two beam splitters to create three beams of light from this which will be my three telescopes. To cancel any difference in path length, the three beams pass through delay lines, after which they are recombined in an optical fibre. This acts as a spatial filter to restore the flat wave front, which has become disturbed by the various optical components. Only the parts of the wave front that are unaffected will pass into the fibre, while the disturbed sections of the wave front are focused outside the fibre. A detector then measures the intensity as a function of the position of the delay lines. The delay lines are moved in increments of 10 nanometre, and the intensity measured at each setting. The set-up is computer-controlled, so the entire phase range can be mapped fully automatically. In this way, some 40,000 (200 x 200) points can be measured within 45 minutes to obtain the two-dimensional interference pattern. My next step will be to measure smaller steps in order to stay closer to the primary minimum. We have already demonstrated that we are able to obtain better attenuation on a star if we introduce phase differences of 2π. The nulling minimum is not as deep as I expected based on the theory, but this might be caused...

In addition to the variation in the position due to lateral translation, there is also a motion in the direction towards and away from the observer, which is seen as a Doppler effect. Measuring the effect as a function of time enables the rotational period of the planet to be determined, among other things.

Two waves of the same light source that are exactly in phase will interfere constructively (left), i.e. they will amplify each other, causing the source to be observed as brighter. However, when the waves are exactly out of phase (right), they will cancel each other, and this is known as destructive interference, and results in the extinction of the light source.

Bracewell’s nulling interferometer. A wave front from the star arrives simultaneously at both telescopes (θ = 0), resulting in destructive interference. The light of the star is extinguished. A wave front from a possible planet arrives at an angle. After passing through the phase shifter, instead of being out of phase, these waves will sometimes even be fully in phase, resulting in amplification of the planet’s brightness. If the star’s image is attenuated sufficiently (approximately one million times), the planet will come into view.
by an imperfect matching of the beams. In places where the beams do not overlap, there is no interference, and no minimum.’

Mieremet is optimistic: ‘I have demonstrated theoretically that an attenuation factor of one million can be achieved with just a single dispersive material. I am confident that, given the right conditions, we won’t need any dispersive material at all, and that delay lines are sufficient to obtain the desired phase shifts. This will make the optics a lot simpler, cheaper, and more reliable.’ So we can kill two birds with one stone, since the use of multiple telescopes will result in wider minimums (which will also attenuate the edges of the star) that are also deeper (provide greater attenuation). The fact that the results would be wider was already known, but the deeper minimums in the interference pattern is a new result. This discovery by Mieremet means that achromatic phase shifters can now be constructed much easier.

Professor Braat is pleased: ‘This is a welcome bonus, since few materials exist that allow high-quality transmission of infrared over a large bandwidth. Using these materials, it is very difficult to construct a pure achromatic phase shifter comprising two or more elements.’

Darwin
Sometime around 2015, the European Space Agency (esa) expects to launch the darwin space telescope. The darwin project will comprise six independent telescopes arranged in a hexagonal pattern around a central satellite in which all the light beams will converge. The distance between the telescopes is several dozen, even hundreds of metres. Metrological systems will equalise all the optical path lengths to an accuracy of a few nanometres. Delay lines and achromatic phase shifters can then be used to introduce phase differences and so obtain nulling. The primary mission of darwin will be to search for Earth-like exoplanets around the thousand stars closest to us. In addition the telescope will also be used for imaging objects, e.g. dense gas and dust clouds in which stars are born. darwin will scan the infrared range, from approximately 5 to 20 micrometres, the wavelength range in which the starlight outshines a planet about one thousand times less than in the visible part of the spectrum. This wavelength range also contains the spectral lines of water, oxygen, methane, and carbon dioxide, which may point to the presence of life. Achromatic phase shifting currently is the subject of a number of different concurrent studies. Ultimately, esa will compare the various results, and use the best technology for darwin. It looks like Delft might be holding a winner.

This research was carried out in the framework of the Knowledge Centre for Optical Aperture Synthesis, an institute founded by TU Delft and TNO/TPD.

For more information, please contact

---

Since the Bracewell nulling interferometer was unable to sufficiently attenuate the edges of the star, a third telescope was added.

Spectra of Venus, Earth and Mars. The presence of ozone (O3) is regarded as a possible sign of life. Venus and Mars do not show this characteristic.
Test set-up by Arjan Mieremet to verify the principle of the dispersive phase shifter. In the foreground is a mirror that reflects the light in the direction of the dispersive glass sheets. These sheets ensure that each wavelength is subjected to a different delay. By selecting the right combination of glass types and thicknesses, a phase shift between both beams of 180 degrees can be achieved. The controls on the far left and right can be used to accurately adjust the orientation of the glass sheets and so change the path length through the glass sheets at the submicrometre level. The delay line is at the back. Light enters the delay line through the lower holes, and after a number of reflections, exits through the top holes to be focused on a CCD camera.
To understand the behaviour of the phase shifter better, a lattice was used to split the interference pattern into its component colours. Fourier analysis of these patterns ought to have produced results that matched the thicknesses of the glass sheets. Unfortunately, the accuracy of the method proved to be insufficient.
The interference pattern (top) Mieremet managed to generate on the CCD camera without using a phase shifter. It shows a bright white line or fringe in the centre of the pattern. With the phase shifter added to the set-up (bottom), the centre shows a dark fringe. This demonstrates that although the phase shifter works in principle, it does not yet achieve the quality requirements set by Mieremet.
By redeveloping the nulling interferometry theory, Mieremet discovered that the errors in a $\delta$ phase shifter can be cancelled partially by introducing a $2\delta$ phase shifter. Since the errors in both phase shifters are correlated, this results in improved attenuation of the star.

A general view of the new set-up

A schematic diagram of the newly developed set-up in which the delay lines act as phase shifters. Mieremet intends to use this set-up to demonstrate that the nulling of a light source is easier to achieve with a phase shifter path difference of approximately $0$, $\delta$ and $2 \delta$ radians (none, half a wavelength, and a whole wavelength) rather than a $0$, $\delta$, $0$ phase distribution. The difference with the previous set-up is that the dispersive phase shifter has been removed and that a third beam has been added. This set-up has already been used to demonstrate the correctness of Mieremet’s theory.
The core of the set-up. The beam arriving from the left is split into three beams using two beam splitters (nos. 1 and 2). Each beam passes through a delay line so the total path length can be adjusted. Then the beam splitters are used to recombine the beams, which leave the set-up at beam splitter no. 3.

The recombined beam is focused on a glass fibre, which is connected to an intensity meter that registers the attenuation of the source.

Based on the theory he had developed, Mieremet calculated the intensity of the recombined beam as a function of the differences in path length between the beams. If all differences in path length are equal \((x = 0, y = 0)\), constructive interference will result, and the expected beam intensity will be high (red). On the other hand, if the path lengths are not equal, this may result in amplification or attenuation (blue). The lower the measured intensity, the better the attenuation of the light source.
The theoretical expectations were confirmed by the measurements. The pattern is almost identical to the calculated one.

An artist’s impression of the DARWIN mission which is expected to be ready for launch around 2015. The Darwin project consists of six telescopes arranged in a hexagon. At the centre of the hexagon is a seventh satellite that collects and combines the beams from the six telescopes. The centre satellite will also contain the achromatic phase shifters. A separate communication satellite will be used to send the collected data back to Earth. The measurements using this telescope array combination cannot be performed on Earth due to atmospheric and thermal disturbances.
Close-up view of one of the six telescopes. The satellites feature a sun shield (with a diameter of 7.4 metres) which ensures that the temperature of the telescope does not rise above approximately 40 K in order to suppress thermal noise effects. The beam of light collected by the primary mirror (1.5 metres diameter) exits the telescope in the direction of the central satellite.

Close-up view of the central Darwin satellite in which the six light beams are to be combined.