



AFRL-AFOSR-VA-TR-2022-0018

Rotationally shearing interferometer for extra-solar system planet detection

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10/29/2021
Final Technical Report

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REPORT DOCUMENTATION PAGE*Form Approved*
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PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**1. REPORT DATE (DD-MM-YYYY)**
29-10-2021**2. REPORT TYPE**
Final**3. DATES COVERED (From - To)**
01 Aug 2018 - 31 Jul 2021**4. TITLE AND SUBTITLE**

Rotationally shearing interferometer for extra-solar system planet detection

5a. CONTRACT NUMBER**5b. GRANT NUMBER**
FA9550-18-1-0454**5c. PROGRAM ELEMENT NUMBER****6. AUTHOR(S)**

Marija Strojnik

5d. PROJECT NUMBER**5e. TASK NUMBER****5f. WORK UNIT NUMBER****7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**Centro de Investigacione en Optica
Loma Del Bosque #115
Colonia Lomas Del Campestre Leon, 37150
MX**8. PERFORMING ORGANIZATION
REPORT NUMBER****9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203**10. SPONSOR/MONITOR'S ACRONYM(S)**
AFRL/AFOSR IOS**11. SPONSOR/MONITOR'S REPORT
NUMBER(S)**
AFRL-AFOSR-VA-TR-2022-0018

12. DISTRIBUTION/AVAILABILITY STATEMENT

A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES**14. ABSTRACT**

We demonstrated experimentally, and developed theoretical analysis in support of the proposal, that the rotationally shearing interferometer (RSI) may detect a faint (invisible) distant / point object next to a bright, large object. With this technique the presence of an invisible point object is detected by observing

straight fringes. The presence is confirmed unequivocally by the RSI feature that a change in one parameter produces a change in the detected fringe pattern, but only in the presence of an invisible point object.

We hypothesized that the RSI may be used as an instrument to detect a planet in a nearby solar system

in a technique that causally relates the planet detection with a change of a single parameter under the observer's control, the orientation of the Dove prism in the RSI. Namely, the off-axis planet produces straight fringes whose density increases, and the angle of inclination decreases with the angle of rotation of the Dove prism in the RSI. The star generates a uniform wave front that is invariant to the change in the orientation angle of the Dove prism.

This may be contrasted with the technique that has discovered so far the largest number of planets. With the passage method, the planet passage in front of the star differentially (by a very small amount) changes the amount of radiation that the star appears to be emitting.

We report successful experimental results of the technique to detect an extrasolar planet using an RSI. For the demonstration we designed a simulated solar system, that includes a planet and a star. It consists of two laser beams, each expanded, collimated, and superimposed. We use a beam combiner to offer the simulator as the input in infinity to the RSI. We confirm experimentally the theoretical prediction that the off-axis planet produces straight fringes whose density increases and the angle of inclination decreases with the angle of orientation of the Dove prism in the RSI. The star generates a uniform wave front that is invariant to the angle of the orientation of the Dove prism. The angle of orientation of the Dove prism is under control of the experimentalist; therefore, the number of fringes may be controlled from the Earth to causally confirm (or negate) the planet existence.

We performed both the theoretical and the experimental work. We built a solar system simulator, and the RSI. We demonstrated that the proposed technique of using an RSI to detect a planet indeed works in the laboratory environment. For the laboratory demonstration, we designed and developed a single aperture instrument under the stringent conditions of the Mach-Zehnder configuration. We developed theory of operation of the RSI in this configuration. We discovered some interesting properties of the RSI, including that the angular derivative function is only valid for the lowest order aberrations.

Four papers were published in peer-reviewed journals, and 9 peer-reviewed conference proceedings, 4 of those invited. They represent the deliverables. Our center underwent a series of reorganizations. Most non-essential work was stopped in March 2020. P.I. initiated collaborations with the scientists at the Univ. of Guadalajara.

15. SUBJECT TERMS**16. SECURITY CLASSIFICATION OF:****a. REPORT****b. ABSTRACT****c. THIS PAGE**

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17. LIMITATION OF ABSTRACT

SAR

18. NUMBER OF PAGES

29

19a. NAME OF RESPONSIBLE PERSON

GEOFFREY ANDERSEN

19b. TELEPHONE NUMBER (Include area code)

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final Report for AOARD Grant

FA9550-18-1-0454

Rotational shearing interferometer for extra-solar planet detection

10/21/2021

Period of Performance: 08/01/2018 – 07/31/2021

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FA9550-18-1-0454
 Rotational shearing interferometer for extra-solar planet detection
 Centro de investigaciones en Optica, A. C., Leon, Mexico
 Marija Strojnik, P.I.

ABSTRACT

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We hypothesized that the RSI may be used as an instrument to detect a planet in a nearby solar system in a technique that causally relates the planet detection with a change of a single parameter under the observer's control, the orientation of the Dove prism in the RSI. Namely, the off-axis planet produces straight fringes whose density increases, and the angle of inclination decreases with the angle of rotation of the Dove prism in the RSI. The star generates a uniform wave front that is invariant to the change in the orientation angle of the Dove prism. This may be contrasted with the technique that has discovered so far the largest number of planets. With the passage method, the planet passage in front of the star differentially (by a very small amount) changes the amount of radiation that the star appears to be emitting.

We report successful experimental results of the technique to detect an extrasolar planet using an RSI [2]. For the demonstration we designed a simulated solar system, that includes a planet and a star. It consists of two laser beams, each expanded, collimated, and superimposed. We use a beam combiner to offer the simulator as the input in infinity to the RSI. We confirm experimentally the theoretical prediction that the off-axis planet produces straight fringes whose density increases and the angle of inclination decreases with the angle of orientation of the Dove prism in the RSI. The star generates a uniform wave front that is invariant to the angle of the orientation of the Dove prism. The angle of orientation of the Dove prism is under control of the experimentalist; therefore, the number of fringes may be controlled from the Earth to causally confirm (or negate) the planet existence.

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1. M. Galan, M. Strojnik, and Y. Wang, "Design method for compact, achromatic, high- performance, solid catadioptric system (SoCatS), from visible to IR," *Optics Express* **27**, No. 1 | 7 Jan 2019 | OPTICS EXPRESS 142. <https://doi.org/10.1364/OE.27.000142>
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Table of Content

FA9550-18-1-0454

Rotational shearing interferometer for extra-solar planet detection

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Marija Strojnik, PI

Page	Section
2	Abstract
3	Table of Content
4	I Introduction
7	II Theory
10	III Experimental
13	IV Results
13	IV.1 Laboratory demonstration of detection of a weak off-axis signal in the presence of strong one with RSI
16	IV.2 Theory of the RSI
16	IV.3 Throughput (etendue) improvement
17	IV.4 Signal-to-noise improvement
17	IV.5 Optical system characterization
18	V Discussion
18	V.1 Excellent project results
18	V.2 Covid 19 and experimental work in Mexico
18	V.3 Request for reports
19	VI Plans for next option period
20	VII References
21	VIII Deliverables
21	(a) Papers published in peer-reviewed journals
22	(b) Presentations at international congresses with proceedings
23	(c) papers published in non-peer-reviewed journals and conference proc.
23	(d) conference presentations without papers
23	(e) manuscripts submitted but not yet published
23	(f) List any interactions with USAF Research Laboratory, other US scientists/institutions or significant collaborations that resulted from this work
23	(g) Graduated students
24	(h) Invited and keynote conference presentations
25	(i) Awards and honors P.I.
26	(j) Participants and their Orchid ID
	Appendix 1: AFOSR membership
	Appendix 2: Report reminder
	Appendix 3: CIO account balance (US\$46,329.16)
	Attachments (1): Four (4) refereed, published papers, three (3) refereed published conference papers, one (1) refereed accepted conference proceedings paper
	Attachments (2): Report receipt confirmations for year 2 (2020) and year 1 (2019)

I. Introduction

During the last thirty years the interest in potential solar systems outside our own has grown significantly. The number of techniques that has been developed increases every day, resulting in dedicated missions and new proposals for astronomical planet observatories. During the early observational work, the astronomers have looked for the stars that display some characteristics that qualify them as variable stars. Over 4000 planets have been discovered so far. Figure 1 illustrates the planet detection problem. The planet search has inspired us to investigate more general research into detection of a faint signal in presence of a strong one.

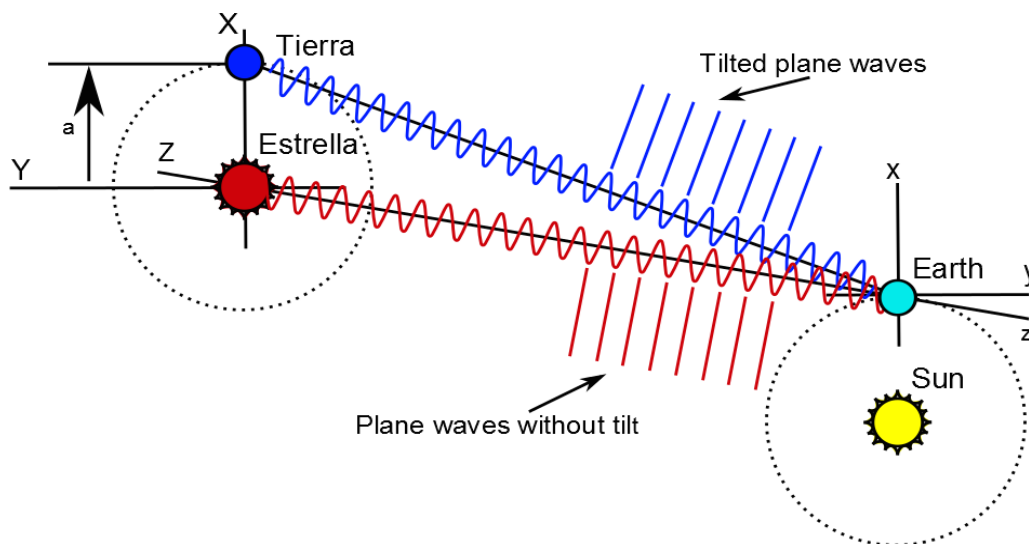


Fig. 1. Geometry for the detection of a planet outside our Solar system. The Earth-based coordinate system is given as a Cartesian system (x,y,z) , while the nearby Planetary system is displaced along the optical axis, Z -axis, with the Cartesian coordinates (X, Y, Z) . Nearby solar system includes a star, that we call Estrella, and a planet, named Tierra, in this simplest geometry, because all the nearby stars already have a name.

The current observational techniques to detect planets outside our solar system allow us to detect something different, unusual, and even extraordinary, employing state-of-the-art instruments, primarily telescopes [1]. However, only future instruments may confirm whether it is indeed a planet, a collapsed star, a dust cloud, or a bunch of rocks or asteroids in a potential asteroid belt or even a future planet. The most successful method of planetary discovery has been the so-called transition, where the passage of a planet in front of the star or behind it results in a small change in its total emission of the radiation, as detected on the Earth. Other natural phenomena may result

in a change of radiation in a forward direction and be detected on Earth. An example of a phenomenon that results in a change of total energy emitted in a forward direction is a prominence, or even an interaction of the solar wind with the matter.

One problem with the established planet-detection techniques is that the change in radiation is small, variable, and may not necessarily be caused by an orbiting planet. The scientists measure a small change in emitted power and postulate the existence of a planet. Even the proposals for the future telescopes, as well as the current James Webb telescope to be sent into the space before the end of year, essentially employ the established techniques, using improved detectors, larger signal-collection area, and better imaging environments.

Also, planets (for example, those in our own solar system) take a long time to orbit their star, so long measurements in time are required to confirm the existence of the planet. Due to the difficulty of lengthy and precise radiative measurements, most discovered planets have short-time orbits (on the order of an earth week), and they orbit red giant stars in a near orbit.

The first objective of this research is the demonstration of a novel planet-search technique to find a more repeatable and reliable method. Then the planet existence would result in a predictable, repeatable, and reliable instrument response that could subsequently confirm planet existence by the original research team or other teams. One such proposed technique is to an RSI. This device is an infrequently used interferometer that compares a wavefront with a modified version of itself after the wavefront has been rotated by an angle.

An RSI is considered a wavefront derivative technique. Derivative techniques have always been popular in high precision measurements, as for example in the radiometric measurement with the lock-in amplifier, where a signal may be buried under six orders of magnitude larger uniform noise. If the noise is constant, then a derivative technique exposes only a small signal.

An RSI takes a derivative of the signal with respect to the angle to isolate the angular direction of the incoming radiation. If the field of view includes a source with the same phase for all angles (namely, that the same phase does not change with angle, then its derivative is zero. We can say that the RSI does not detect anything. This case is representative of the guide star that is located in the center of the field.

If another source is located in an off-axis position within the field of view, then its phase is not invariant with respect to the azimuthal angle. Its derivative is not zero, so it stands out, that is, it is detectable. A planet is located off-axis, so it is detectable when the RSI is bore sighted on the star.

When the RSI has the planet in its field of view in addition to the centered star, the RSI detects it, even though its signal is much smaller than the star's signal.

The long-term goal of this research is to apply the detection technique to any two non-equal intensity signals that are either point signals or sufficiently distant from the detection plane that they may be considered point sources. For example, the space station is not sufficiently distant from the Earth surface, because we can see with an unaided eye that it has width, that is, it is not a point source as seen from the Earth. It would be a point source as seen from any other planet in our solar system. A satellite may be considered a point source. If it has a small, companion, the satellite will be a brighter object in the infrared spectral band, because its thermal capacity is higher, and it will be warm due to all the electronics working inside. Such a companion may be detected with an RSI. This is the second potential application of the research.

An additional goal is the secure communication through the space during daytime, and despite some jamming, between any two points with the unobstructed line-of-sight between them.

The side benefit of this research is the improvement of the testing techniques of the so-called free-form optical surfaces that are defined by the high-order polynomials that require establishment of novel measurement and testing techniques.

II. Theory

The search for a planet outside our solar system pushes the limits of the radiometric and angular resolution of the detecting instrument. In the detection scenario, the search for the extra-solar planet considers our solar system as the search object, while the instrument is located at a nominal distance of 10 parsecs, a relatively small value in comparison with that of many discovered solar systems.

The angle between the planet and the star subtends $2 \mu\text{rad}$, illustrated in Fig. 2. At that distance, the star and the planet subtend a half-angle of 10^{-4} and $10^{-5} \mu\text{rad}$, respectively, at the Earth. They are considered point sources. Due to large propagation distances, the emitted spherical waves transform into plane waves. This is also in agreement with the van Cittert-Zernike theorem that further states that such waves also become coherent.

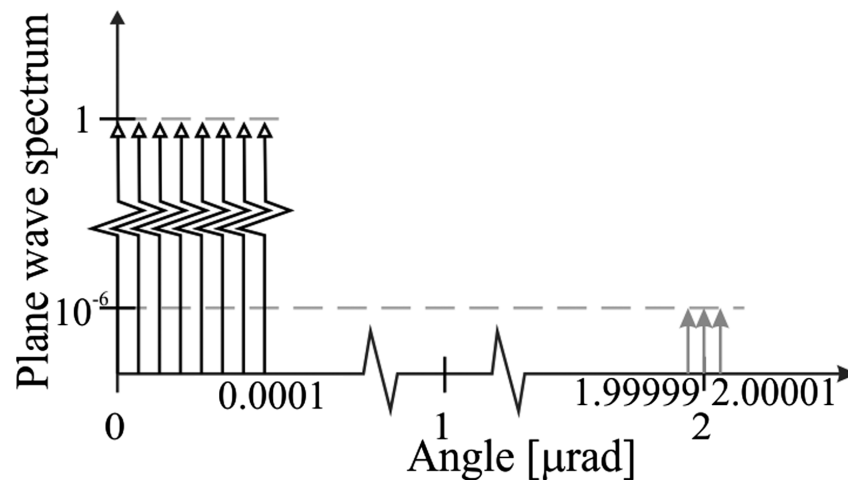


Fig. 2. A solar system, including a Sun-like star and a Jupiter-like planet at 10 parsecs, subtends an angle of $2 \mu\text{rad}$ at the Earth. At that distance, the star and the planet subtend at the Earth an angular radius of 10^{-4} and $10^{-5} \mu\text{rad}$, respectively.

A distant solar system consisting of a star and a planet generates two plane waves. An RSI detects only those wave fronts that do not possess cylindrical symmetry [2, 4]. We performed a simulation study of the fringe patterns obtained with the RSI when detecting a star and a planet at a potential nearby solar system. The results of the simulations are exhibited in Fig. 3. The simulations with different shear angles demonstrated that the density of the straight fringes increases, and their slope decreases upon increasing the shear angle; that is, twice of the angle of rotation of the Dove prism.

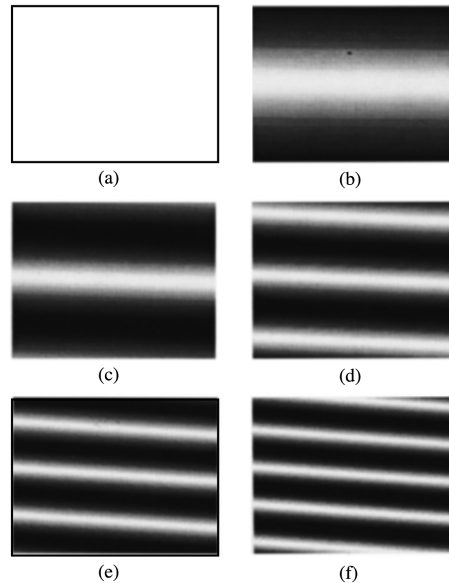


Fig. 3. Interference fringes of tilt simulated in an RSI when the shear angle is increased from 0 (blank field) to 8° in increments of 1.6° (normal to the image). The density of fringes increases, and the fringe inclination angle decreases with increasing shear angle.

The incidence pattern arising from two wave fronts may be obtained in a two-beam interferometer. We express the wave fronts and the incidence patterns in a cylindrical coordinate system for an RSI where a wave front in one arm is rotated by an angle $\Delta\phi$ with respect to the wave front in the other arm.

$$u_{ps}(\rho, \varphi) = S + P \exp(ikl\rho \cos\varphi) \quad (1)$$

The wave u_{ps} is the combined signal from the star and the planet. S and P are related to the intensities (power per unit solid angle) of these two sources through the square of the inverse distance; l denotes the direction cosine of the wave coming from the planet. The theoretical derivation has been published for a two-aperture interferometer previously. Here we summarize the theoretical development for the performance of a single aperture instrument, leaving out the factor of 4 for 50/50 beam-splitters and Fresnel losses.

$$M_{psT}(\rho, \varphi) = SS^* + \frac{PP^*}{2} [1 + \cos(kl\rho\Delta\varphi\sin\varphi)] \quad (2)$$

Equation 2 is the mathematical expression that demonstrates the feasibility of planet detection using an RSI. When the planet is present next to a star, and we change the shear angle, $\Delta\varphi$, the fringe separation decreases and the number of fringes increases, according to $\rho \sin\varphi = \lambda / l\Delta\varphi$. The sun provides the background signal, considered a noise. If we subject the image to advanced signal processing that is customary in astronomy, the variable signal due to the planet will be enhanced. In the absence of the planet's radiation, the incidence reduces to the star's self-interference.

$$M_{psT}(\rho, \varphi) = \frac{SS^*}{2} (1 + \cos\gamma) \quad (3)$$

Here, we use γ to denote the phase difference between the interferometer arms. The incidence in the detection plane reduces to the planet self-interference in the absence of the star radiation.

$$M_{psT}(\rho, \varphi) = \frac{PP^*}{2} [1 + \cos(kl\rho\Delta\varphi\sin\varphi + \gamma)] \quad (4)$$

The angle of the Dove prism, $\Delta\varphi$, appears in the numerator of the argument of the cosine function. Thus, the number of fringes increases with the increase in the shear angle.

These expressions demonstrate that the off-axis planet generates tilt fringes due to the incidence of the inclined plane waves with respect to the RSI axis. The on-axis star introduces no fringes, only a uniform field when the RSI is aligned on the star. The very presence of the fringes confirms the existence of a planet. The increase in the fringe density upon the increase in the shear angle $\Delta\varphi$ causally confirms the presence of an off-axis source, that is, a planet. Furthermore, it greatly diminishes the possibility of an artifact being erroneously interpreted as a planet.

III. Experimental

A simulated planetary system is coupled to the RSI, implemented as a modification of the Mach-Zehnder interferometer [2]. The planetary system is indicated on the left of Fig. 4. The star laser and its beam-conditioning components are carefully aligned to the RSI axis. The planet laser-beam is placed at a slight angle with respect to the star laser beam. It is rotated with a beam turning mirror and coupled to the star laser beam with a cube beam combiner.

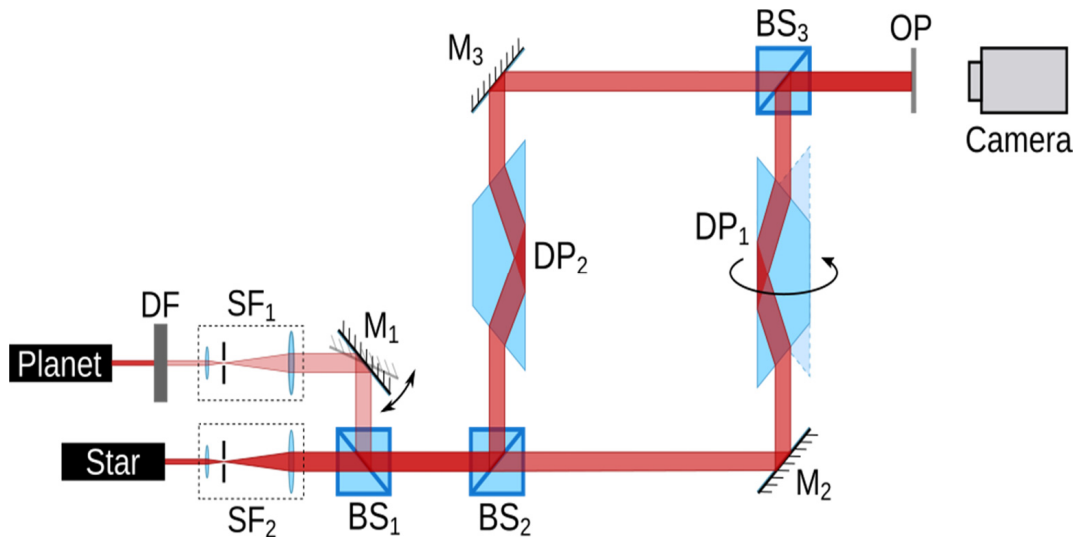


Fig. 4. The experimental layout includes a simulated planetary system (left) and the RSI (right). The simulated solar system includes two point sources. The star beam is aligned to the RSI optical axis. The planet beam is inclined with respect to the star beam. A Dove prism that is rotated by an angle about the optical axis introduces the wave-front shear in the RSI. The components are denoted as follows: Star & Planet denote lasers that simulate the respective point sources, DF is a neutral density filter, SF is a spatial filter, M is a mirror, BS is a beam splitter, DP is a Dove prism, and OP denotes the observation plane.

A second cube beam splitter divides the incident wave fronts into two beams and sends them into two interferometer arms. A Dove prism in each arm transforms the interferometer into an RSI. A rotated Dove prism rotates the wave front in one interferometer arm with respect to that in the other arm. 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 third beam splitter. The interferograms are captured with a high-resolution 4,000 by 4,000-pixel Apogee camera and stored in a PC. There, the incidence distributions may be processed further.

The schematic diagram in Fig. 4 is not to scale. Figures 5 and 6 present the photos of the solar system simulator and the RSI, respectively, to provide a reference for the dimensions.

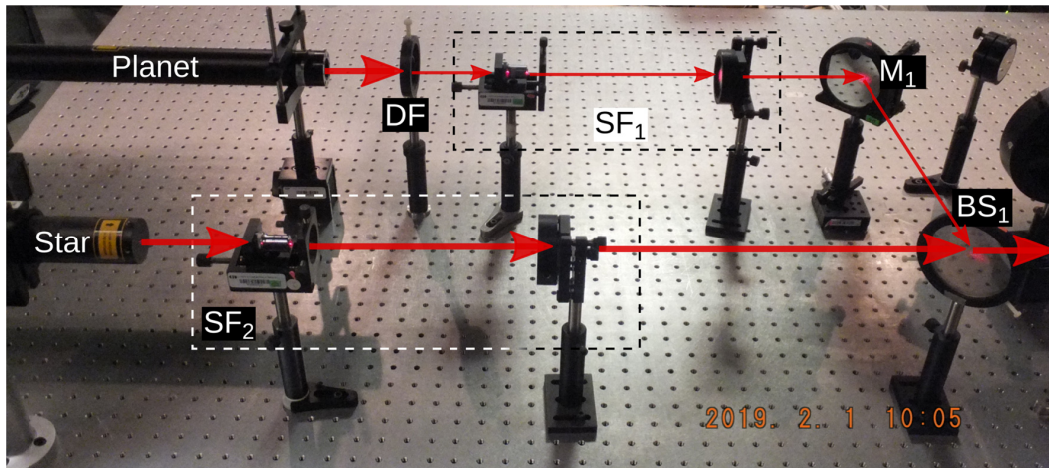


Fig. 5. The photograph of the solar system simulator shows the lasers, the beam conditioning optics, and the turning mirror that (mis)aligns the planet laser. The solar system simulator is coupled into the RSI through the beam splitter BS1.

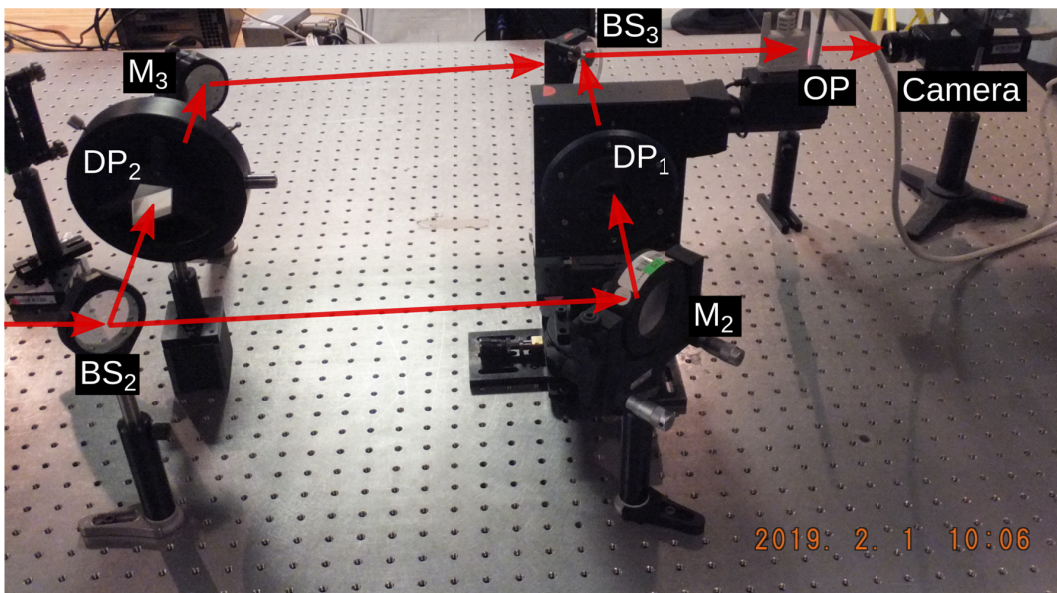


Fig. 6. The photograph of the RSI illustrates the second beam splitter (the first beam splitter in the interferometer), a high-quality Dove prism in its precision rotary mount, a compensatory prism, both turning mirrors, the second beam splitter in the interferometer, and a camera.

The planet and star are simulated with the 1.5-mW and 12-mW HeNe lasers, both from Newport. The optical components are 5-cm in diameter, fabricated by Edmund Sci. and Thorlabs, Inc. The most challenging component to fabricate is the Dove prism whose high tolerances limit its commercial availability to 2.5-cm aperture. It is also the component that limits the beam throughput. Edmund makes the off-the-shelf mounts, including the ones for the lasers, while PI Motion (Physik Instrumente) supplied the rotary mount. Computer controls will improve the interferometer precision in future implementation. The names of suppliers are for information purposes only.

IV. Results

1. Laboratory demonstration of detection of a weak off-axis signal in the presence of strong one with an RSI. In Fig. 7, we display the interferograms obtained with the experimental setup of Fig. 4 when the angle of rotation of the Dove prism increases from 0 to 20 degrees. We present three cases: (i) only the star laser is on, (ii) only the planet laser is on, and (iii) the complete solar system simulator is on, that is, the star and the planet lasers.

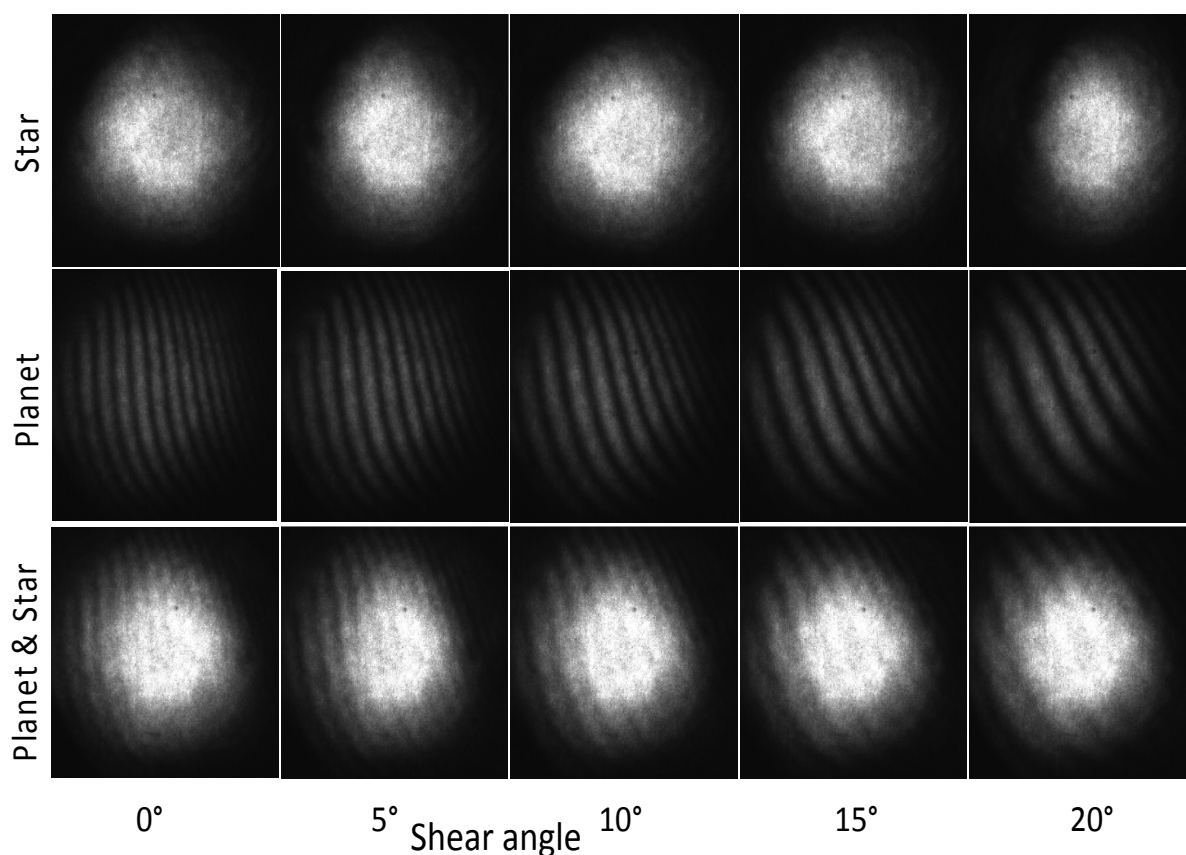


Fig. 7. The interferograms of the simulated solar system obtained in the RSI when the shear angle increases in four equal increments from 0 to 20 degrees. The first row shows the case of the laser source on the optical axis. The second row presents a faint laser source slightly off-axis. A decrease in the number of fringes and a decrease in fringe slope are observed with the increase in the shear angle. The third row features the interferograms when both the on-axis and off-axis source are turned on. These interferograms are very similar to those of planet-only interferograms, except that the star incidence floods the central portion of the interferogram. The observation of fringes that change with shear angle confirms the presence of the planet.

In the first row, the interference patterns do not change when the shear angle increases for a single point source on the optical axis. This series of experiments confirms that the RSI is insensitive to the star on the optical axis. A single bright fringe is detected. No pattern rotation is observed when the incident star wave front possesses rotational symmetry. This is the case for a star without a planetary companion when the instrument is aligned with the star center. Indeed, there is no rotation of the fringe pattern with the change in the orientation angle of the Dove prism, indicating a perfect alignment of the star beam on the RSI axis.

In the second row, the interference patterns indeed 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 nearly straight interference fringes decrease in density and increase in inclination angle when the shear angle is augmented. This is one of the defining characteristics of the RSI in measuring the tilted wave fronts. This experimental data confirms that an off-axis source can be detected in an RSI by generating straight fringes. 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. This verification step is under the control of the experimentalist and repeatable.

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 very similar to the planet-only interferograms, except that the star incidence floods the central portion of the interferograms, a consequence of the Gaussian shape of the laser incidence. Filtering the constant background would diminish the star noise effects.

The planet presence may be confirmed by observing the straight fringes. The fringe visibility decreases in the central part of the interferogram for the raw, unprocessed measurements. The fringes decrease in density and increase in their angle of inclination when the shear angle is increased. These are the characteristics of a tilted wave front as measured in the RSI.

Thus, our experimental data confirms that a dim off-axis source next to a bright source can be detected in an RSI. The dim source generates faint fringes on top of mostly uniform bright star incidence, as predicted by the theory. Figure 8 presents a graph of the measured number of fringes as a function of the shear angle. Figure 9 displays the measured fringe-pattern angle upon increasing the shear angle. They confirm the feasibility of the proposal that an RSI may be used to

detect an invisible planet orbiting a nearby star, should there be one.

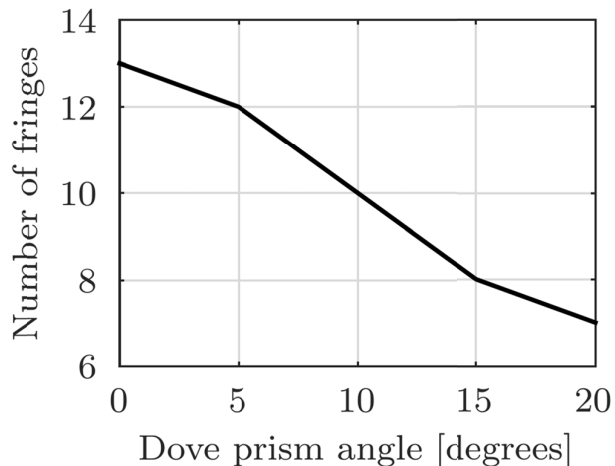


Fig. 7. The measured number of fringes as a function of the shear angle.

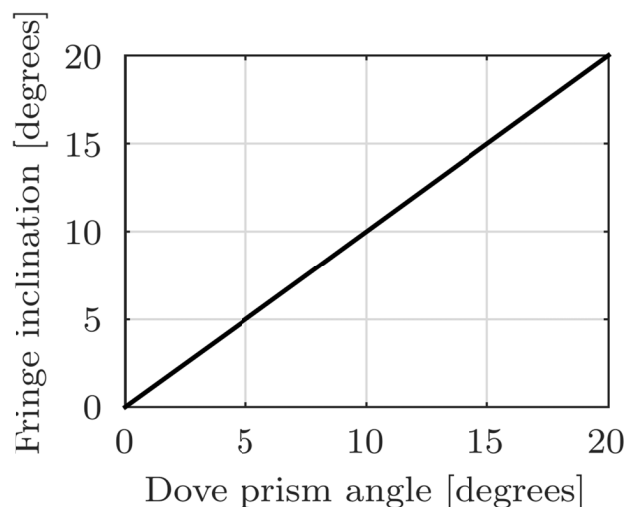


Fig. 8. The measured fringe-inclination angle as a function of the shear angle.

We designed and built a simulated extra-solar planetary system. It consists of two essentially parallel laser beams, incorporating beam-expanders, a turning mirror, and a cube beam combiner to superimpose them at the entrance to the RSI. The beams are coupled into the RSI with a beam combiner cube. The star laser is aligned to the optical axis of the RSI.

We demonstrated the feasibility of detecting a planet in a simulated solar system using an RSI in the laboratory setting. We confirmed that the off-axis planet indeed produces straight fringes whose density changes with the shear angle. The star produces a uniform field that is invariant to

the change in the shear angle. The fringe-density decrease and the increase in fringe-pattern inclination angle, when caused by the changes in the angle of orientation of the Dove prism, confirm the presence of a planetary companion.

IV.2. Theory of the RSI. Originally, the concept of the RSI interferometry to detect planets was presented as a two-aperture interferometer, each aperture to function as a free flyer. This configuration could not be simulated in a laboratory, so our RSI was conceived as a modified Mach-Zehnder interferometer. Its layout incorporates a single aperture. Two beams still travel along different paths to modify the wavefronts rotationally. After the experiment performed in the laboratory setting performed as originally predicted, a concern arose whether this implementation also was performing as a derivative of the wavefront with respect to the angle. During the institute closure, we developed an original theory of the performance of the single-aperture RSI and applied it to the planet detection problem. It was originally published as an SPIE proceedings paper and later expanded to become a refereed publication [3]. This analytical development starts with wavefront expansion into spherical harmonics, finding that the RSI is indeed insensitive to some aberrations. Finally, we developed novel analytical expression for the incidence (power per unit area) in the observation plane.

IV.3. Throughput (etendue) improvement. The experimental technique to detect a point source flooded by illumination from a bright source on the optical axis represents a significant advance in signal detection and processing technique. Our next concern was how to increase the signal quality by increasing the throughput. The most difficult optical component in the optical train to fabricate is actually the Dove prism, an equal side prism with the top part cut-off to decrease weight. We studied the design of massive optical devices that do not change their dimensions and performance as we change wavelength from the visible range to the infrared. We focused on a telescope design with no moving parts, in contrast with the current James Webb telescope [1]. The telescope might be placed on the far side of the Lunar surface where planetary observations might be feasible for 9 out of 12 months, obstructing the light noise and heat from the Earth civilization.

The fabrication and acquisition of the Dove prism itself represents a critical step in the design of the next generation RSI. A retroreflector prism of 1-m aperture was already fabricated and left on the Moon during the Apollo missions to measure the Moon-Earth distance for the next fifty

years. For two 2-inch prisms we obtained one in-house quote and one from China, but both stopped the fabrication process at the beginning of year 2020. Once the prisms are acquired, we can proceed with their testing and evaluation.

Finally, we are exploring the fabrication of larger-aperture Dove prisms that do not have the weight issue. We are looking at fabricating an array of small prisms whose combined aperture would represent an increase in aperture area, with all of them changing their physical orientation at the same time [5]. We are evaluating their aberrations. They could be made small, corresponding to the best possible commercial grade. The top surfaces would be coated for absorption and cemented together, while the bottom surfaces would have to be coated as mirrors and then likewise cemented. The segmented wavefront would then be reconstructed digitally.

IV.4 Signal-to-noise improvement. During the experimental work, it became clear that further coherence issues needed to be explored to interpret the quality of measured results. We determined that a partial decrease in coherence of the sources rapidly destroys the visibility of the fringe patterns [4,6]. Furthermore, we found the laser stability to be a problem in the measurements of the fringes because they move. We demonstrated that the interferometer under the conditions of perfect temporal and spatial coherence would result in recognizable interferometric patterns even for multiple planets orbiting the same star [7].

IV.5 Optical system characterization. An additional area of research that we wanted to address with respect to the ability of the RSI to perform as well as theoretically predicted the quality of optical components that are needed to make the RSI a high precision instrument for absolute measurements. Namely, when it is used as an interferometer in a comparison setup, the optical fabrication errors in two paths are approximately the same and they cancel out in some degree. In the RSI for the planet detection, we cannot anticipate that the errors will compensate, so we are performing analysis of infrared optical systems in off-axis configuration which has not yet been done. All such analyses have been last performed over forty years ago with many simplifying assumptions [8].

V. Discussion

V.1 Excellent project results. The feasibility of the proposed detection of a faint point object next to a bright point object has been successfully demonstrated in the laboratory, using a simulated solar system. This constitutes a success of the method, with several technological issues becoming apparent during the experimental work. Most of them required theoretical research and design tradeoff considerations. These were undertaken and accomplished with outside collaborators during the Covid-19 closure of the institute for about 1.5 years.

V.2 Covid 19 and experimental work in Mexico. Mexican government agency, the Conacyt, closed the access to the National Research Centers for about 18 months, a decision that made it impossible to continue the laboratory work. The contract monitoring officer was advised of the intention to ask for a non-cost extension in March2020, due to the covid-19 restrictions.

V.3 Request for reports. The AFOSR sent to the P.I. the request for final reports [Appendix 2]. According to the CIO accountant, unspent funds remain (US\$46,329.16) [Appendix 3]. The AFOSR can recuperate these funds, possibly send them to some University, for example, the University of Guadalajara where the planet detection research is progressing well and where the P.I. intends to guide her two Ph. D. students to graduation.

VI. Plans for next option period

There are several theoretical and design research issues that are recently becoming resolved, mentioned in results, but not yet published. These MSs will be written up and published next year.

The first small new experiment that requires acquisition of new components will be a of commercially available Dove prisms, that will be combined into an array of 2 by 3 prisms with an increased aperture, suitably coated on top and bottom of each prism for transmission and reflection, and glued. This new segmented prism will then be tested. Depending on the outcome of this experiment, the next generation RTI with an increased aperture will be designed, assembled, aligned, and demonstrated, still employing increased-diameter, commercially available optical components.

The critical components that incorporate the adjustments in positions and orientations of the optical components will be set under computer control, starting with the orientation of the Dove prisms. This will increase the stability of the interference pattern, allowed sequences of images necessary for image processing and averaging, and determination of most favorable experimental parameters. The lasers will be replaced with those with better stability and coherence. Furthermore, we will implement an optical path module in each interferometer arm to assure the highest degree of path equalization. This task requires an engineering graduate with knowledge of control mechanisms. We plan to collaborate with the team from the University of Guadalajara.

Finally, we will further decrease the radiance of the planet laser to obtain fainter fringes and implement signal-processing techniques to detect fainter fringes. This task requires a computer engineering graduate with knowledge of image processing methods. We plan to collaborate with the team from the University of Guadalajara.

VII. References

1. M. Galan, M. Strojnik, and Y. Wang, "Design method for compact, achromatic, high-performance, solid catadioptric system (SoCatS), from visible to IR," *Optics Express* **27**, No. 1 | 7 Jan 2019 | OPTICS EXPRESS 142. <https://doi.org/10.1364/OE.27.000142>
2. M. Strojnik, B. Bravo-Medina, "Rotationally shearing interferometer for extra-solar planet detection: preliminary results with a solar system simulator," *Optics Express*, Vol. 28(20), 28 September 2020. <https://doi.org/10.1364/OE.398649>
3. R. Gonzalez-Romero, M. Strojnik, and G. Garcia-Torales, "Theory of a rotationally shearing interferometer," Vol. 38 (2) / February 2021 / 264-270, *JOSA-A*. <https://doi.org/10.1364/JOSAA.406186>
4. B. Bravo-Medina, M. Strojnik, A. Mora-Nuñez, H Santiago- Hernández, "Rotational-Shearing-Interferometer response for a star-planet system without star cancellation," *Appl. Sci.* **2021**, *11*, 3322. <https://doi.org/10.3390/app11083322>
5. R. Gonzalez-Romero, G. Garcia-Torales, and M. Strojnik, "Numerical analysis of microlens array to the mid-IR range," *Proc. The 16th International Workshop on Advanced Infrared Technology and Applications (AITA 2021)*, Florence, Italy, 26 - 28 October 2021. (In publication.)
6. M. Strojnik and B. Bravo-Medina, "Response of rotational shearing interferometer to a planetary system with two planets: simulation," *Invited, Proc. SPIE 11057, Modeling Aspects in Optical Metrology VII*, 1105705 (21 June 2019); <https://doi.org/10.1117/12.2526331>
7. M. Strojnik and M. Bravo-Medina, "Simulation of extrasolar planet detection with rotationally shearing interferometer at 10 μm ," *Invited, Proc. The 15th International Workshop on Advanced Infrared Technology and Applications (AITA 2019)*, Florence, Italy, 17-19 September 2019. doi:10.3390/proceedings2019027044
8. M. Strojnik, Y. Wang, "Ensquared energy and optical centroid efficiency in optical sensors," *Invited, ICOL 2019 (XVIII Symposium of Optical Society of India)*, Dehradun, India, Oct. 19-22, 2019.

VIII. Deliverables

a) Papers published in peer-reviewed journals

1. M. Galan, M. Strojnik, and Y. Wang, “Design method for compact, achromatic, high-performance, solid catadioptric system (SoCatS), from visible to IR,” *Optics Express* **27**, No. 1 | 7 Jan 2019 | OPTICS EXPRESS 142. <https://doi.org/10.1364/OE.27.000142>
2. M. Strojnik, B. Bravo-Medina, “Rotationally shearing interferometer for extra-solar planet detection: preliminary results with a solar system simulator,” *Optics Express*, Vol. 28(20), 28 September 2020. <https://doi.org/10.1364/OE.398649>
3. R. Gonzalez-Romero, M. Strojnik, and G. Garcia-Torales, “Theory of a rotationally shearing interferometer,” Vol. 38 (2) / February 2021 / 264-270, *JOSA-A*. <https://doi.org/10.1364/JOSAA.406186>
4. B. Bravo-Medina, M. Strojnik, A. Mora-Nuñez, H Santiago- Hernández, “Rotational-Shearing-Interferometer response for a star-planet system without star cancellation,” *Appl. Sci.* **2021**, *11*, 3322. <https://doi.org/10.3390/app11083322>

b) Presentations at international congresses with proceedings 08-01-2018 to 7-31-2021

1. M. Strojnik and B. Bravo-Medina, "Response of rotational shearing interferometer to a planetary system with two planets: simulation," *Invited*, Proc. SPIE 11057, Modeling Aspects in Optical Metrology VII, 1105705 (21 June 2019); <https://doi.org/10.1117/12.2526331>
2. B. Bravo-Medina, M. Strojnik, A. Mora-Nuñez, "Image inverting interferometer for extra-solar planet detection," Proc. SPIE 11128, Infrared Remote Sensing and Instrumentation XXVII, 1112805 (9 September 2019, Optical Engineering, San Diego, California, USA). <https://doi.org/10.1117/12.2526138>
3. M. Valero, M. Strojnik, I. Salgado-Transito, "Design, manufacturing and testing of a CPV + T based on a Cassegrain: trough configuration," Proc. SPIE 11128, Infrared Remote Sensing and Instrumentation XXVII, 111280Z (9 September 2019, Optical Engineering, San Diego, California, USA). <https://doi.org/10.1117/12.2527482>
4. B. Bravo-Medina, M. Strojnik, E. Ipus, (2019) "Comparison of nulling Interferometry and rotational shearing interferometry for detection of extrasolar planets," *Progress in Optomechatronic Technologies, Springer Proceedings in Physics, vol 233*, A. Martínez-García, I. Bhattacharya, Y. Otani, and R. Tutsch (Eds.), Springer, Singapore, ISBN: 9789813296312. https://doi.org/10.1007/978-981-32-9632-9_22
5. M. Strojnik, "When aberrations carry useful information," Proc. SPIE 11479, Roland V. Shack Memorial Session: A Celebration of One of the Great Teachers of Optical Aberration Theory, 114790J (21 August 2020); <https://doi.org/10.1117/12.2570988>
6. M. Strojnik, "Many facets of interferometry: a deceptively simple and powerful measurement technique," Proc. SPIE 11813, Tribute to James C. Wyant, 118130R (4 August 2021); <https://doi.org/10.1117/12.2570482>
7. M. Strojnik, "Optimal wavelength interval for extra-solar planet detection," Proc. SPIE 11830, Infrared Remote Sensing and Instrumentation XXIX, 1183008 (1 August 2021); <https://doi.org/10.1117/12.2598439>
8. M. Montes-Flores, G. Garcia-Torales, M. Strojnik, "A lab proof-of-concept of an extrasolar planet detection using a rotationally shearing interferometer," Proc. SPIE 11830, Infrared Remote Sensing and Instrumentation XXIX, 118300O (1 August 2021); <https://doi.org/10.1117/12.2595095>
9. M. Strojnik, "Rotationally shearing interferometry in the recovery of faint signals," Proc. SPIE 11830, Infrared Remote Sensing and Instrumentation XXIX, 1183007 (1 August 2021); <https://doi.org/10.1117/12.2598438>

c) Papers published in non-peer-reviewed journals and conference proceedings,

none

d) Conference presentations without papers

9. M. Strojnik, Y. Wang, “Ensquared energy and optical centroid efficiency in optical sensors,” *Invited*, ICOL 2019 (XVIII Symposium of Optical Society of India), Dehradun, India, Oct. 19-22, 2019.
10. M. Strojnik, G. Garcia Torales, “Displacement interferometry in recovery of small signals,” *Invited*, Annual Meeting, Mexican Physical Society, Michoacan, Mexico, Oct. 5 – 9, 2020 (virtual).

e) Conference proceedings manuscripts accepted but not yet published

1. R. Gonzalez-Romero, G. Garcia-Torales, and M. Strojnik, “Numerical analysis of microlens array to the mid-IR range,” *Proc. The 16th International Workshop on Advanced Infrared Technology and Applications (AITA 2021)*, Florence, Italy, 26 - 28 October 2021.

f) List any interactions with USAF Research Laboratory, other US scientists / institutions or significant collaborations that resulted from this work

1. No collaboration with the scientists from the USAF Research Laboratory on this research, although met several in San Diego 2019 SPIE conference for casual interchanges; some of them longtime associates, in different specialties of optics
2. Dr. Yaujen Wang, retired from Martin-Marietta Co., still collaborating
3. Collaboration with the University of Guadalajara, including equipment exchanges

g) Graduated Doctoral Students

1. Maximiliano Galan Gonzalez, “Limitas de deteccion de planetas extra-solares con un interferometro de desplazamiento rotacional: condiciones” (Limits in planet detection using a rotational shearing interferometer: conditions), June 2019, Tecnologico de Monterrey, Leon, Mexico

Graduated Master-of-Science Students

1. Sergio G. Angulo, “All-in-focus image reconstruction robust to ghosting effect”, Feb 2019. Doctoral Student.
2. Erick Fabian Ipus Bados, “Limit of application of the method of ballistic photons in biological tissue”, Sept. 2019. Doctoral student.
3. Marcos Valero, “Comparison of adaptive optics,” Nov. 23, 2020. Optical Research Center; Dec. 15, 2020, Electro-optics, University of Dayton, Ohio. Double degree student. Doctoral student.

h) Invited and keynote conference presentations

1. M. Strojnik and B. Bravo-Medina, “Response of rotational shearing interferometer to a planetary system with two planets: simulation,” *Invited*, Proc. SPIE 11057, Modeling Aspects in Optical Metrology VII, 1105705 (21 June 2019); <https://doi.org/10.1117/12.2526331>
1. B. Bravo-Medina, M. Strojnik, T. Kranjc, “Feasibility of planet detection in two-planet solar system with rotationally-shearing interferometer,” *Invited*, Proc. SPIE 11128, Infrared Remote Sensing and Instrumentation XXVII, 111280F (9 September 2019, Optical Engineering, San Diego, California, USA). <https://doi.org/10.1117/12.2538817>
3. M. Strojnik and M. Bravo-Medina, “Simulation of extrasolar planet detection with rotationally shearing interferometer at 10 μm ,” *Invited*, Proc. *The 15th International Workshop on Advanced Infrared Technology and Applications (AITA 2019)*, Florence, Italy, 17-19 September 2019. doi:10.3390/proceedings2019027044
4. M. Strojnik, A. Beltran-Gonzalez, G. Garcias-Torales, B. Bravo-Medina, “Portable device to monitor skin conditions with diffuse, multi-spectral illumination,” *Invited*, RIAO (Ibero-American meeting on optics), Cancun, Mexico, Sept. 22 – 27, 2019.
5. M. Strojnik, Y. Wang, “Ensquared energy and optical centroid efficiency in optical sensors,” *Invited*, ICOL 2019 (XVIII Symposium of Optical Society of India), Dehradun, India, Oct. 19-22, 2019. (Trip paid by the SPIE)
6. M. Strojnik, G. Garcia Torales “Displacement interferometry in recovery of small signals,” *Invited*, Annual Meeting, Mexican Physical Society, Michoacan, Mexico, Oct. 5 – 9, 2020 (virtual).

i) Awards and honors P.I.

Journal Editorial Activities

- 2017 – pres. Deputy Editor, 1st & 2nd term, *Optics Express*, OSA, USA
2019 -- 2020 Lead Guest Editor, *Applied Optics*, Advanced IR technology & applications, OSA
2018 – 2021 Chair and Proceedings Editor, *Infrared Technology, and Instruments*, XXVII, XXVIII, and XXIX
2019, 2021 Chair and Editor, *Advance Infrared Technology and Applications* 2019, 2021

Honors

- 2021 Featured in Updated Temporary Exhibition of 13 Slovenian American scientists, Philadelphia, Ohio
2017-19 Featured in Temporary Exhibition of Slovenian Technical Museum of 13 scientists
2017-19 Featured in booklet accompanying Exhibition of Slovenian Technical Museum

Awards

- 2021 Fellow of Sigma Xi
2021 Fellow, Academia Mexicana de Optica
2019 Election to SNI Emerita (220 in total Mexico)

j) Participants and their Orchid ID

	Name		Orchid number
1	Marija Strojnik	Distinguished Professor Optical research Center	https://orcid.org/0000-0003-1000-6468
2	Ricardo Gonzalez-Romero	Instructor University of Guadalajara	https://orcid.org/0000-0002-7092-5370
3	Guillermo Garcia-Torales	Full Professor University of Guadalajara	https://orcid.org/0000-0002-3556-6480
4	Azael Mora-Nuñez	Assistant professor University of Guadalajara	https://orcid.org/0000-0002-4675-5228
5	Héctor Santiago-Hernández	Assistant professor University of Guadalajara	https://orcid.org/0000-0002-3438-9224
6	Beethoven Bravo-Medina	Assistant professor University of Guadalajara	https://orcid.org/0000-0002-5999-4404
7	Yaugen Wang	Retired, Martin-Marietta Corp.	
8	Maximilian Galán	Professor Technologico de Monterrey	
9	Gilberto Gomez-Rosas	Department head, Physics University of Guadalajara	

Appendix 1: AFOSR membership

APAN Community: Membership Denied: AFOSR

1 mensaje

APAN Community - Automated Email <noreply@apan.org>
Para: Marija Strojnik <marias@cio.mx>

21 de octubre de 2021, 08:03

Update from APAN Community [<https://community.apan.org/>]

Unfortunately, your membership request to the AFOSR group couldn't be approved at this time.

Appendix 2: Report Reminder

AFOSR <noreply@qemailserver.com>
Reply-To: AFOSR <technicalreports@us.af.mil>
To: MARIJA STROJNIK <mstrojnik@gmail.com>

Tue, Oct 19, 2021 at 1:44 F



Air Force Office of Scientific Research

*****You may have received a Qualtrics generated email without any additional instructions. If you have already filed your report via APAN (<https://community.apan.org/wg/afosr/p/deliverables>) please disregard this reminder and the previous email reminder. We are sorry for any inconvenience this may have caused. Please contact us if you have questions or need additional assistance at technicalreports@us.af.mil *****

STROJNIK, MARIJA

This is a reminder that you have a: Final Performance report that is due to AFOSR on 10/29/2021. The award number for this report is: FA9550-18-1-0454.

Please Follow this link to the Survey and complete at your convenience:
Take the Survey

Appendix 3: CIO accounting (balance in account, US\$46,329.16)

Yoana Elizabeth Tejeda Portillo <yoana.etp@cio.mx>
Para: Strojnik Pogacar Marija <marias@cio.mx>
CC: Jefatura de Contabilidad <jefatura.contabilidad@cio.mx>

20 de octubre de 2021, 09:31

Buen día Dra Marija

Por indicaciones de la CP Angélica Baeza, le comento que en la cuenta de este proyecto hay un monto de 46,329.16 Dólares al 30 de Septiembre, aproximadamente son \$964,575.69 pesos.

Cualquier otra duda o comentario, estoy a sus órdenes.

Saludos cordiales...

El mié, 20 de oct. de 2021 a la(s) 10:33, Jefatura de Contabilidad (jefatura.contabilidad@cio.mx) escribió: