Abstract—The current interests in extra-solar planet detection and space-based and ground-based interferometry for astronomical observations has led to the development of a number of nulling instrument designs at the Jet Propulsion Laboratory (JPL) and elsewhere. This paper summarizes briefly JPL’s efforts in nulling interferometry to date and consists of illustrations of some key nulling activities. Basic layouts of nulling testbeds are described and key applications discussed. Some notable nulling efforts made elsewhere will not be included, in an effort to narrow the area of discussion.

1. INTRODUCTION

While a great many extra-solar planets have been detected by indirect observations, key science questions cannot be answered unless planet photons can be separated from the dominant stellar photon flux. For example, the size and temperature of the planet can be measured from its infrared and optical spectra and atmospheric gases will contribute absorption lines to those spectra, enabling composition measurements to be made. Such measurements are critical in the search for evidence of extra-solar life. While the radial velocity technique (the most successful planet finding extension of these results to broadband and randomly found in nature.stellar objects) can be used to detect planets, it does not directly detect planet photons. This need has led to the development of starlight suppression techniques such as nulling interferometry and nulling coronagraphy. These techniques drastically reduce the stellar photon flux either by carefully correcting optical aberrations in large but otherwise fairly conventional telescopes, or, in the case of nulling interferometry, by utilizing the slight phase gradient of the planet light to divert it into a separate path.

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In a conventional telescope, optical imperfections cause light from the star to fall onto regions of the image plane where a planet would be seen, thus drowning out the planet image. In a nulling coronagraph, the optical imperfections are carefully corrected using a deformable mirror and the direct starlight is also attenuated by a combination of pupil plane apertures and focal plane masks. The result is a dark field in the focal plane from which starlight is excluded, enabling planets within that region to be detected unambiguously.

In a nulling interferometer, an array of telescopes [1] is used to collect the light. Pairs of telescopes are used to null the starlight, effectively diverting it from the main beam train. The planet light has a slightly different phase difference from the starlight measured across the telescope pair, and it is constructively interfered so that it remains in the main beam train. After this process, a significant photon background remains, so the planet light is modulated by adding additional nulling telescope pairs. This allows subtraction of the photon background.

There are of course a number of variations of the techniques in terms of geometry and in beam combination methods. A nulling interferometer based on a single telescope is also being studied which combines features of the coronagraph and telescope arrays. This paper will describe the principal starlight suppression technologies being investigated at the Jet Propulsion Laboratory, and will summarize recent results, future plans and outline mission concepts for the detection of extra-solar rocky planets.

Deep nulls of narrowband light have been achieved using both pupil-plane and focal plane nulling techniques. The extension of these results to broadband and randomly polarized sources is now the principal challenge. This paper will review some of the technical efforts currently in progress at the Jet Propulsion Laboratory aimed at nulling light sources with optical properties more similar to those found in nature.

To achieve deep nulls in an interferometer, the optical properties of the combined beams must be quite similar. The properties include intensity balance, polarization angle, polarization dispersion, and rms wavefront differences. Some of the requirements for the balance in these properties can be mitigated by the use of single mode spatial filtering at the detector, for example by using a single mode fiber to
receive the light. The components of a typical optical system will introduce defects into the pristine wavefront received from the stellar source, adding wavefront deformations and polarization changes. If these defects are more or less the same in each input beam of the interferometer, the system will still be capable of nulling. For a broadband source the defects need to be controlled across the entire nulling waveband and this places additional requirements on the optical system design. At JPL, these requirements have been addressed with the development of the Adaptive Nuller [2] which is a system designed to correct intensity and phase differences across the band for both polarizations.

Deep laser nulls in the visible waveband of order $10^5$ with deeper transients were reported by Martin et al [3]. The source polarization was controlled as part of the null optimization process. That testbed, known as the SIM rooftop nuller, was also used for some broadband nulling tests. It utilized a geometric field inversion technique but was asymmetric in that a beamsplitter-compensator plate arrangement was used. A more symmetrical nuller was then built, the modified Mach-Zehnder nuller [4] (MMZ) in which field inversion was performed outside the nuller and the beams traversed two beam splitters each, allowing symmetrical treatment. The Keck nuller [5] employs two MMZ nullers to null four input beams. More recently, laboratory work has utilized Mach-Zehnder schemes to produce symmetrical nulling systems for the Planet Detection Testbed (PDT) [6] and the Achromatic Nulling Testbed (ANT) [7], for example. The PDT has nulled four laser beams at 10.6 μm wavelength at the 250,000 to 1 level. Work on PDT is aimed at demonstrating stable infrared nulling and faint planet detection while ANT is focused on broadband nulling and polarization insensitivity.

A somewhat different interferometric beam combination scheme was proposed in Europe [8]. By combining beams directly on a single mode fiber, the complex interaction of the light with beamsplitter and antireflection coatings can be eliminated. Conceptually, such a beamcombiner can be both achromatic and polarization insensitive, at the cost of some optical throughput efficiency. Small scale testbeds for this type of beamcombiner are now being developed at JPL both for laboratory investigations and for operation on telescopes.

2. NULLING RESULTS

A graphical depiction of nulling results was recently prepared by Peter Lawson [9] showing nulling results to date which were known to him from various workers around the world. A subset of this data formed the basis of this discussion on nulling technology at JPL. This graph (figure 1) shows nulling results for narrow-band and broadband nulling, and at different wavelengths with an
indication of the time when the results were published. It gives an impression of the similar progress achieved in visible nulling compared with what would appear to be the less challenging field of infra-red nulling. Infra-red nulling would appear to be easier because the requirements on wavefront control, phase control, and beam alignment for example are roughly 5 times less challenging at 10 microns than at 500 nm wavelengths. Also, it’s noticeable that the performance (with the exception of one recent datapoint) is relatively poor in broad-band nulling. This graph of course skips many of the important details such as length of time over which a null was averaged and the question of unpolarized or polarized detection.

The work by other researchers in the field should not be overlooked, and details of some of the nulling results achieved elsewhere can be found in references [10], [11] & [12].

3. NULLING TECHNOLOGY

SIM rooftop nuller

SIM, the Space Interferometer Mission, is scheduled for launch in the next decade. Though now excluded from the plan, a nulling instrument was proposed for the mission and this led to the construction of the rooftop nuller shown in figure 2. The main objective was to demonstrate deep nulls up to 1,000,000 to 1 at visible wavelengths. The key feature of the nuller is the use of rooftop mirrors to perform the electric field inversion. (Nulling interferometry in essence combines two incoming beams, one being phase-inverted so that destructive interference takes place.) This geometric field inversion has the advantage of being achromatic, but it also inverts the pupil, so that two beams that may be slightly dissimilar will be interfered. This effect is probably of most significance only in the laboratory since it could cause reduced performance with light sources of some angular size. In space, the star would normally be unresolved, so the source effectively has no size.

The nuller employs a beamsplitter/compensator plate arrangement and a single aperture at the output of the beamsplitter. The single aperture avoided reflections from the rooftop joint and allowed control of the relative intensity of the two input beams. The input beam was fed to the system via a single mode fiber and allowed to expand before collimation by an achromatic lens. The fiber was mounted in a gimbal so that its optical axis could be angled with respect to the optical axis of the nuller. The single output pupil traced back through the system to the entrance forms two input apertures, and by angling the fiber, the relative intensity of the light entering each input could be accurately controlled by using an incandescent source with <0.1% short term intensity variation.

Keck Nuller

The Keck nuller was developed for the observatory in Hawaii and utilizes four input apertures derived from the two primary mirrors of the twin telescopes. Observations are currently being made in the infra-red N-band (~8 to 12 μm) An inherently more symmetrical layout was used. In the rooftop nuller there are asymmetries in the two beam paths in terms of numbers of anti-reflection coatings traversed and types of reflections, internal versus external. The modified Mach-Zehnder layout is more symmetric [15] with respect to beam paths. In the ideal MMZ nuller a single beamsplitter is cut into two halves, and one half reversed with respect to the other. In this implementation, four beamsplitters were made as nearly identical as possible and
arranged in custom-designed dual mounts. Mirrors are arranged around the two splitters as shown in figure 4. All the reflections and transmissions take place at the same angle of incidence, 30°, an angle chosen to reduce the reflectivity differences between the s and p polarizations which are encountered in beamsplitter design.

Figure 4- Layout of the modified Mach-Zehnder nuller.

To produce the field inversion, the Keck nullers use the phase plate method [14] which can be simply described as follows. In one of the two beams, a thickness of glass $d$ is introduced so that $(n-1)/d = \lambda/2$, where $n$ is the refractive index and $\lambda$ is the wavelength. Then the increased refractive index in the glass retards the phase in one beam relative to the other, producing a $\pi$ phase change resulting in the desired field inversion. In fact for observations through the atmosphere, the Keck experiment requires larger phase shifts to compensate for chromatic dispersion in the atmosphere, and the $\pi$ phase change is a small additional term in the correction. The Keck nuller as a whole is a complex system and will not be described here. Readers are referred to references [16], [17] & [18].

Results from the laboratory set-up were obtained addressing broadband infra-red nulling [19] and laser nulling [4] respectively at around 10 $\mu$m wavelength. At 18% bandwidth, null depths of 20,000:1 were achieved and using polarized laser light, nulls of 2 million to one; shown in figure 5.

Figure 5- Two million to one nulling with polarized light at 10.6 $\mu$m on an MMZ nuller.

Visible nulling coronagraph

For infrared nulling intended for planet detection around nearby stars, the baseline (the distance between the collecting telescopes) needs to be quite large. For example, to place a null fringe on the star and a constructive fringe on the planet requires a baseline of $\lambda/2a$ where $a$ is the angle made by the planet. For a star at 10 pc with a planet orbiting at 1 au, this angle is 0.1 arc sec (0.5 $\mu$r), and so for N-band (10 $\mu$m) nulling, the baseline will be around 11 m. For nulling in the visible, the baseline will be dramatically reduced to around 0.6 m, so the observations can be made from a single telescope platform. To gather sufficient light, the apertures must be larger than the baseline so the shearing geometry of the nulling coronagraph nuller [20] was developed. For example to detect a Jupiter-like planet, the aperture needs to be about 1 m, and to detect an Earth-like planet, 8 m. Figure 6 shows the layout of the nuller. The lower rooftop mirror is used to vary the baseline on the telescope mirror, and the right rooftop mirror is used to modulate the delay.

Figure 6- Visible nulling coronagraph layout
For achromatic nulling, a \( \pi \)-radian phase shift is needed across the band. This can be achieved using pairs of glass plates (known as phase plates) of different types and thicknesses. In this case we are minimizing the integral:

\[
\int_{\text{passband}} \left( n_1(\lambda) \cdot d_1 + n_2(\lambda) \cdot d_2 + d_a \right) / \lambda + \pi \right)^2 d\lambda \tag{1}
\]

where the \( n_s \) are the refractive indices and the \( d_s \) are the thicknesses of the two glasses and any additional free space. This expression can readily be solved numerically and optimal solutions can be found. The combination of BK7 and fused silica optical glasses, for example, gives a very deep theoretical null of approximately 10,000,000:1 across the band 500 to 800 nm.

Figure 7 – Simple Mach-Zehnder nuller

Mach-Zehnder nuller

To attempt deep nulls in a simplified geometry, the coronagraph nuller was copied but the roof-top mirrors were replaced with flats as shown in figure 7. This nuller then has the basic functions of a source, source beamsplitter, and a detector and nulling beamsplitter. Dual phase plates were included to allow broadband nulling and the whole system was placed inside a sealed container. After being allowed to settle for more than 12 hours, very deep and stable nulls could be achieved. Figure 8 shows laser nulling at 9 million to 1. Broadband nulls at 15% bandwidth at or near 1 million to 1 have also been recorded. (At the time of writing these results are unpublished).

Figure 8 – A deep laser null of order \( 10^7 \)-1 obtained on the simplified coronagraph Mach-Zehnder nuller.

4. FIBER BEAM COMBINERS

Fiber nuller

Beam combination directly on the fiber (figure 9) was first proposed only a few years ago. Such systems have the merit of simplicity, requiring no well-controlled coatings such as are needed on beamsplitter combiners, but they pay a price with reduced throughput because of under-filling of the fiber’s field of view. This can be improved upon by adding more apertures; four apertures can yield a reasonable coupling efficiency. Another issue concerns stability of the null. For small offsets \( \alpha \) from normal incidence and disturbances to that offset \( \beta \), it can be shown that the coupling efficiency varies with:

\[
1 - \left( \frac{\alpha}{d_0} \right)^2 \left( a^2 + 2abs(\omega t) + b^2 \cos^2(\omega t) \right) \tag{2}
\]

where \( \omega \) is the characteristic frequency of the disturbance and \( d_0 \) is a property of the fiber. For the case of oblique incidence, \( a \) is non-zero, leading to a greater sensitivity to perturbations of the alignment.

However, despite the novelty of the fiber nulling approach, deep narrowband nulls near one million to one [21] (figure 10) have already been achieved using such beamcombiners, and broadband nulls near 10,000 to one at 18% bandwidth (1.5 to 1.8 \( \mu \)m H-band) [22], so these simple combiners are likely to produce good results in the future.
Figure 9- Nulling near 1,000,000 to 1 using a single mode fiber beam combiner and a HeNe laser source.

Figure 10- Nulling near 1,000,000 to 1 using a single mode fiber beam combiner and a HeNe laser source. See reference [hagenauer]

Currently a fiber nuller is being constructed for K-band (2.2 μm) nulling at the Mt. Palomar telescope in California. Models of the coupling efficiency show that pupil densification is desirable to avoid too much loss. The plan is to aperture the collimated beam from the telescope with two circular apertures and null the beams on a single mode fiber using phaseplates to produce a broadband field inversion. If the separated pupils are compressed ("densified") using an optic designed to bring the pair of pupils closer together, the coupling efficiency of the nulling light to the fiber rises from 16% to 45%. Figure 11 shows the point spread function at the focus for the two cases of densified and undensified apertures. In the densified case, more of the energy appears at the center of the fringe pattern and is available to be coupled into the fiber.

Figure 11- Upper set: Point spread function and aperture geometry for the telescope pupil. Lower set: the same for a densified pupil.

5. IMAGE PLANE NULLING

The preceding descriptions are concerned with interferometric nulling of collimated beams, but it is also possible to use nulling techniques at the focal plane. An occulting device is placed at the focus of a coronagraph to block the intense light from the center of the field of view. If the object is a star, a very small occulting disc is needed. The disc can be replaced by a nulling device which cancels the starlight in the center of the far field, thus facilitating detection of faint companion objects which are normally invisible because of glare. Two examples follow, one which has been used for observations, and another which is in the concept stage.

Four quadrant phase mask

The four-quadrant phase mask (FQPM) is a transparent optical mask with four quadrants of different thicknesses arranged to induce relative phase shifts of 0, π, 0 and π, traveling clockwise around the mask; see figure 12. Since the phase mask can be made large it works independently of image size (assuming the image is free of aberrations), but for simple single step masks has limited achromaticity. The modified incoming beam expands from the focus and is recollimated. At the next Fourier plane the light from the center of the mask appears at the edges of the pupil and can be blocked using an aperture (known as the Lyot stop). After reimaging, the image has a four-fold symmetry with a dark central null, see figure 12. On the Palomar telescope, a bright binary star was nulled using this technique (figure 13) to show its faint companion star [23].
Optical vortex

An optical vortex is a device which produces a helical wavefront. Light near the center of the vortex experiences a large phase gradient and is thrown tangentially away from the center. Light near the edges of the mask experiences little gradient and is transmitted with less deviation. If such a mask were placed at the focus of a telescope pointed at a star, the starlight would be tangentially radiated so that the bright, central portion could be blocked by a Lyot stop in the exit pupil plane. Nearby companion objects, although they would suffer some distortion would not be blocked by the stop and would be imaged in the following focal plane. Ideally such a device would be made achromatic so as to obtain a deep null over a reasonable optical bandwidth. In practice, optimizations of model vortexes using ray tracing software have not yet revealed systems which could be used in the challenging task of earth-like planet detection around nearby stars, but these devices may prove useful in less demanding applications such as the detection of binary companions. However it is possible that other analogous and similar approaches will yield better results. A model of an optical vortex produced in two glasses is shown in figure 14 Rays passing near the center of the vortex can be seen deviated away from the centerline. The figure also shows an example of the ray distribution at the Lyot plane. The innermost rays come from the outer radius of the incoming beam, rays coming from objects further out would pass through the Lyot stop and be imaged on the image plane. More complex systems can also be modeled with achromatizing pairs of vortices, but would pose some manufacturing challenges because the optimum step heights are typically many tens of microns.

6. CONCLUSIONS

Significant progress has been made in nulling technology to reach null depths of 1 million to 1 and better both at infrared wavelengths and in the visible. Good broadband nulling results have been slower to emerge and together with attention to dual polarization nulling point to the desirable direction of effort. Null depths of 1 million to 1 are adequate for planet detection in space in the infrared, while yet deeper nulls (1000x) or some additional technology [20] would be needed for visible detection.

While pupil plane nulling has shown the highest performances so far, the output signal from such a nuller has to be processed to produce an image. Here, the advantages of nulling in the image plane come to the fore, because coronagraph-type nullers will produce realistic (if not exact) images of the area of the sky being viewed. In focal plane nulling, future effort should be directed to achromatic performance, elimination of artifacts such as the quadrant zones of the FQPM, as well as deeper null depths.

This brief survey of some of the nulling technology developed at one laboratory illustrates some of the variety of techniques already conceived to facilitate the detection of faint astronomical objects near bright sources. Nullers are now being deployed at observatories and soon will be on space-based platforms and will no doubt contribute to scientific knowledge about the universe.

7. ACKNOWLEDGEMENTS

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8. REFERENCES


9. Biography

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