

Tunable Kernel-Nulling interferometry for direct exoplanet detection

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ABSTRACT

Nulling interferometry is a promising technique for direct detection of exoplanets. However, the performance of current devices is limited by the sensitivity to phase aberrations. This thesis attempts to overcome those challenges by using a four-telescopes nulling interferometer architecture, called Kernel-Nuller,¹ which includes a recombiner that positions the four signals in phase quadrature. This architecture is based on an integrated optical component containing 14 electronically controlled phase shifters, used to correct optical path differences that would be induced by manufacturing defects. The first part of the study consists in the development of an algorithm providing the delays to be injected into the component to optimize the performance of that device. This technique is first evaluated via numerical simulations, then in lab. It is then envisaged to leverage the Nuller mode, soon to be installed on the VLTI as part of the ASGAR project, to test this architecture under real conditions of observation. The next step of this study deals with the analysis of the intensity distributions produced at the output of the Kernel-Nuller^{1,2} through a series of observations, against which statistical tests and machine learning techniques are applied to detect the presence of exoplanets. The preliminary results of this study are presented in this proceeding.

Keywords: Interferometry, Exoplanet, Kernel-Nulling, VLTI, ASGAR

1. INTRODUCTION

The direct detection of exoplanets is a challenging task due to the high contrast between the star and the planet. Nulling interferometry is a promising technique to overcome this challenge. It consists in combining the light from several telescopes to create destructive interference and cancel the star light and keeping the planet signal. However, the performance of current devices is limited by the high sensitivity to phase aberrations. The thesis that is presented here attempts to overcome those challenges by using a four-telescopes nulling interferometer architecture, called Kernel-Nuller,¹ which includes a series of fourteen thermo-optic phase shifters, used to correct optical path differences that would be induced by manufacturing defects. The first part of the study consists in the development of an algorithm providing the delays to be injected into the component to optimize the performance of that device. This technique is first evaluated via numerical simulations, then in lab. It is then envisaged to leverage the Nuller mode, soon to be installed on the VLTI as part of the ASGAR project, to test this architecture under real conditions of observation. The second step of this study deals with the analysis of the intensity distributions produced at the output of the Kernel-Nuller^{1,2} through a series of observations, against which statistical tests and machine learning techniques are applied to detect the presence of exoplanets. The preliminary results of this study are presented in this proceeding.

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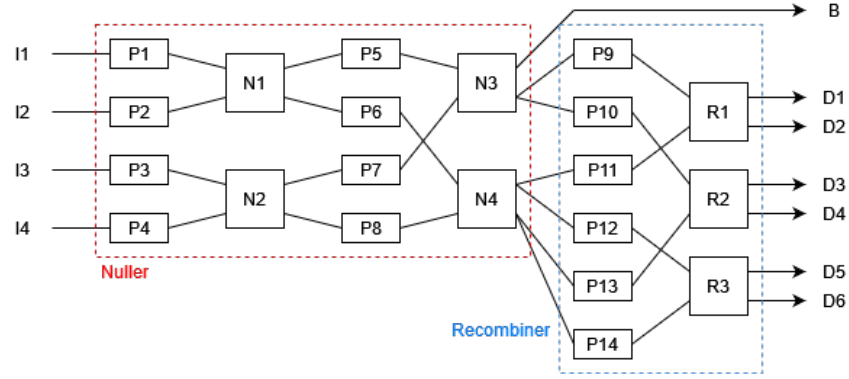


Figure 1. Scheme of the tunable ernel-nuller architecture. P1-14 are the thermo-optic phase shifters. N1-4 represent the four 2x2 Nuller MMI that reproduce a 4x4 one. R1-3 are the three recombiner that place the signals in phase quadrature. I1-4 are the inputs signals. B is the bright

2. FORMATTING OF MANUSCRIPT COMPONENTS

This section describes the normal structure of a manuscript and how each part should be handled. The appropriate vertical spacing between various parts of this document is achieved in LaTeX through the proper use of defined constructs, such as `\section{}`. In LaTeX, paragraphs are separated by blank lines in the source file.

At times it may be desired, for formatting reasons, to break a line without starting a new paragraph. This situation may occur, for example, when formatting the article title, author information, or section headings. Line breaks are inserted in LaTeX by entering `\\` or `\linebreak` in the LaTeX source file at the desired location.

2.1 Title and Author Information

The article title appears centered at the top of the first page. The title font is 16 point, bold. The rules for capitalizing the title are the same as for sentences; only the first word, proper nouns, and acronyms should be capitalized. Avoid using acronyms in the title. Keep in mind that people outside your area of expertise might read your article. At the first occurrence of an acronym, spell it out, followed by the acronym in parentheses, e.g., noise power spectrum (NPS).

The author list is in 12-pt. regular, centered. Omit titles and degrees such as Dr., Prof., Ph.D., etc. The list of affiliations follows the author list. Each author's affiliation should be clearly noted. Superscripts may be used to identify the correspondence between the authors and their respective affiliations. Further author information, such as e-mail address, complete postal address, and web-site location, may be provided in a footnote by using `\authorinfo{}`, as demonstrated above.

2.2 Abstract and Keywords

The title and author information is immediately followed by the Abstract. The Abstract should concisely summarize the key findings of the paper. It should consist of a single paragraph containing no more than 250 words. The Abstract does not have a section number. A list of up to eight keywords should immediately follow the Abstract after a blank line. These keywords will be included in a searchable database at SPIE.

2.3 Body of Paper

The body of the paper consists of numbered sections that present the main findings. These sections should be organized to best present the material. See Sec. 3 for formatting instructions.

2.4 Appendices

Auxiliary material that is best left out of the main body of the paper, for example, derivations of equations, proofs of theorems, and details of algorithms, may be included in appendices. Appendices are enumerated with uppercase Latin letters in alphabetic order, and appear just before the Acknowledgments and References. Appendix A contains more about formatting equations and theorems.

2.5 Acknowledgments

In the Acknowledgments section, appearing just before the References, the authors may credit others for their guidance or help. Also, funding sources may be stated. The Acknowledgments section does not have a section number.

2.6 References

SPIE is able to display the references section of your paper in the SPIE Digital Library, complete with links to referenced journal articles, proceedings papers, and books, when available. This added feature will bring more readers to your paper and improve the usefulness of the SPIE Digital Library for all researchers. The References section does not have a section number. The references are numbered in the order in which they are cited. Examples of the format to be followed are given at the end of this document.

The reference list at the end of this document is created using BibTeX, which looks through the file `report.bib` for the entries cited in the LaTeX source file. The format of the reference list is determined by the bibliography style file `spiebib.bst`, as specified in the `\bibliographystyle{spiebib}` command. Alternatively, the references may be directly formatted in the LaTeX source file.

For books,^{?,?,?} the listing includes the list of authors, book title, publisher, city, page or chapter numbers, and year of publication. A reference to a journal article[?] includes the author list, title of the article (in quotes), journal name (in italics, properly abbreviated), volume number (in bold), inclusive page numbers, and year. By convention,[?] article titles are capitalized as described in Sec. 2.1. A reference to a proceedings paper or a chapter in an edited book[?] includes the author list, title of the article (in quotes), volume or series title (in italics), volume number (in bold), if applicable, inclusive page numbers, publisher, city, and year. References to an article in the SPIE Proceedings may include the conference name (in italics), as shown in Ref. . For websites[?] the listing includes the list of authors, title of the article (in quotes), website name, article date, website address either enclosed in chevron symbols ('<' and '>'), underlined or linked, and the date the website was accessed.

If you use this formatting, your references will link your manuscript to other research papers that are in the CrossRef system. Exact punctuation is required for the automated linking to be successful.

Citations to the references are made using superscript numerals, as demonstrated in the above paragraph. One may also directly refer to a reference within the text, e.g., “as shown in Ref. ...”

2.7 Footnotes

Footnotes^{*} may be used to provide auxiliary information that doesn't need to appear in the text, e.g., to explain measurement units. They should be used sparingly, however.

Only nine footnote symbols are available in LaTeX. If you have more than nine footnotes, you will need to restart the sequence using the command `\footnote[1]{Your footnote text goes here.}`. If you don't, LaTeX will provide the error message `Counter too large.`, followed by the offending footnote command.

3. SECTION FORMATTING

Section headings are centered and formatted completely in uppercase 11-point bold font. Sections should be numbered sequentially, starting with the first section after the Abstract. The heading starts with the section number, followed by a period. In LaTeX, a new section is created with the `\section{}` command, which automatically numbers the sections.

Paragraphs that immediately follow a section heading are leading paragraphs and should not be indented, according to standard publishing style.[?] The same goes for leading paragraphs of subsections and sub-subsections. Subsequent paragraphs are standard paragraphs, with 14-pt. (5 mm) indentation. An extra half-line space should be inserted between paragraphs. In LaTeX, this spacing is specified by the parameter `\parskip`, which is set in `spie.cls`. Indentation of the first line of a paragraph may be avoided by starting it with `\noindent`.

^{*}Footnotes are indicated as superscript symbols to avoid confusion with citations.

3.1 Subsection Attributes

The subsection heading is left justified and set in 11-point, bold font. Capitalization rules are the same as those for book titles. The first word of a subsection heading is capitalized. The remaining words are also capitalized, except for minor words with fewer than four letters, such as articles (a, an, and the), short prepositions (of, at, by, for, in, etc.), and short conjunctions (and, or, as, but, etc.). Subsection numbers consist of the section number, followed by a period, and the subsection number within that section.

3.1.1 Sub-subsection attributes

The sub-subsection heading is left justified and its font is 10 point, bold. Capitalize as for sentences. The first word of a sub-subsection heading is capitalized. The rest of the heading is not capitalized, except for acronyms and proper names.

4. FIGURES AND TABLES

Figures are numbered in the order of their first citation. They should appear in numerical order and on or after the same page as their first reference in the text. Alternatively, all figures may be placed at the end of the manuscript, that is, after the Reference section. It is preferable to have figures appear at the top or bottom of the page. Figures, along with their captions, should be separated from the main text by at least 0.2 in. or 5 mm.

Figure captions are centered below the figure or graph. Figure captions start with the figure number in 9-point bold font, followed by a period; the text is in 9-point normal font; for example, “Figure 3. Original image...”. See Fig. 2 for an example of a figure caption. When the caption is too long to fit on one line, it should be justified to the right and left margins of the body of the text.

Tables are handled identically to figures, except that their captions appear above the table.

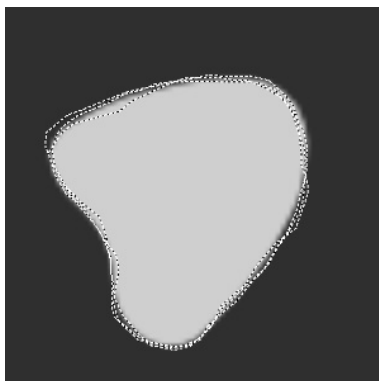


Figure 2. Figure captions are used to describe the figure and help the reader understand its significance. The caption should be centered underneath the figure and set in 9-point font. It is preferable for figures and tables to be placed at the top or bottom of the page. LaTeX tends to adhere to this standard.

5. MULTIMEDIA FIGURES - VIDEO AND AUDIO FILES

Video and audio files can be included for publication. See Tab. 1 for the specifications for the multimedia files. Use a screenshot or another .jpg illustration for placement in the text. Use the file name to begin the caption. The text of the caption must end with the text “<http://dx.doi.org/doi.number.goes.here>” which tells the SPIE editor where to insert the hyperlink in the digital version of the manuscript.

Here is a sample illustration and caption for a multimedia file:

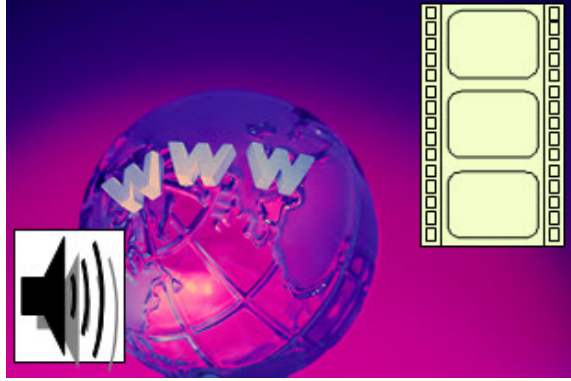


Figure 3. A label of “Video/Audio 1, 2, . . .” should appear at the beginning of the caption to indicate to which multimedia file it is linked . Include this text at the end of the caption: <http://dx.doi.org/doi.number.goes.here>

Table 1. Information on video and audio files that must accompany a manuscript submission.

Item	Video	Audio
File name	Video1, video2...	Audio1, audio2...
Number of files	0-10	0-10
Size of each file	5 MB	5 MB
File types accepted	.mpeg, .mov (Quicktime), .wmv (Windows Media Player)	.wav, .mp3

APPENDIX A. MISCELLANEOUS FORMATTING DETAILS

It is often useful to refer back (or forward) to other sections in the article. Such references are made by section number. When a section reference starts a sentence, Section is spelled out; otherwise use its abbreviation, for example, “In Sec. 2 we showed...” or “Section 2.1 contained a description...”. References to figures, tables, and theorems are handled the same way.

A.1 Formatting Equations

Equations may appear in line with the text, if they are simple, short, and not of major importance; e.g., $\beta = b/r$. Important equations appear on their own line. Such equations are centered. For example, “The expression for the field of view is

$$2a = \frac{(b + 1)}{3c}, \tag{1}$$

where a is the ...” Principal equations are numbered, with the equation number placed within parentheses and right justified.

Equations are considered to be part of a sentence and should be punctuated accordingly. In the above example, a comma follows the equation because the next line is a subordinate clause. If the equation ends the sentence, a period should follow the equation. The line following an equation should not be indented unless it is meant to start a new paragraph. Indentation after an equation is avoided in LaTeX by not leaving a blank line between the equation and the subsequent text.

References to equations include the equation number in parentheses, for example, “Equation (1) shows ...” or “Combining Eqs. (2) and (3), we obtain...” Using a tilde in the LaTeX source file between two characters avoids unwanted line breaks.

A.2 Formatting Theorems

To include theorems in a formal way, the theorem identification should appear in a 10-point, bold font, left justified and followed by a period. The text of the theorem continues on the same line in normal, 10-point font. For example,

Theorem 1. For any unbiased estimator...

Formal statements of lemmas and algorithms receive a similar treatment.

ACKNOWLEDGMENTS

This unnumbered section is used to identify those who have aided the authors in understanding or accomplishing the work presented and to acknowledge sources of funding.

REFERENCES

- [1] Martinache, Frantz, et Michael J. Ireland. "Kernel-Nulling for a Robust Direct Interferometric Detection of Extrasolar Planets". *Astronomy & Astrophysics* **619** (2018): A87. <https://doi.org/10.1051/0004-6361/201832847>.
- [2] Cvetojevic, N. et al. 3-beam self-calibrated Kernel nulling photonic interferometer (2022). Preprint at <http://arxiv.org/abs/2206.04977>.