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NIFITS: BUILDING A NEW DATA STANDARD TO ENABLE THE RISE OF NULLING INTERFEROMETRY

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Abstract. Just as the extreme adaptive optics has enabled the effective use of coronagraphs to detect and characterize exoplanets, the advent of high-precision fringe tracking on our interferometric facilities is opening the door to high-contrast interferometry with nulling beam-combiners. Long-baseline nullers should prove complementary to visible and NIR coronagraphs in the characterization of exoplanets.

Although many nullers have already been commissioned on sky, their usage exploitation has so-far remained a niche practice. One reason for this is that nulling data does not fit in the perimeter of OIFITS standard, making the astrophysical interpretation difficult without the ad-hoc instrument model. The challenge is reinforced by the extreme diversity in the architectures, operating principles and collected observables of both existing and envisioned nullers, including Asgard/NOTT and the LIFE space mission.

With this work, we introduce our efforts to create a new data standard called NIFITS (Nulling Interferometry FITS) to fill this gap. To account for the diversity of present and future instruments, NIFITS encapsulates a complete description of the instrumental transfer function, allowing for a straightforward inference for the user to carry-out model fitting, spectra extraction or even image reconstruction.

Keywords: Interferometry, nulling, exoplanets, high-contrast

1 Introduction

Optical interferometry has offered numerous opportunities to study astrophysical scenes resolving details of the order of milli-arcsecond angular scales and measuring relative astrometry down to a few micro-arcsecond. This has brought countless discoveries such as the measurement of stellar radii and masses (Michelson & Pease 1921), their close environments (Corporaal et al. 2023), but also the on behavior of matter and radiation in extreme gravitational environment (GRAVITY Collaboration et al. 2018, 2020). Yet at high contrast, conventional beam combiners have been limited to the larger separation targets(Lacour et al. 2019).

The study of exoplanets and the growing need to directly resolve and characterize their light poses new challenges to interferometry related to the high contrast of the scenes. This contrast difficulty has been tackled for single-dish imagers with the use of coronagraphs, which create focal planes from which the light coming from the on-axis source has been removed. In interferometry, an equivalent feat is accomplished by nulling beam-combiners which use specific beam phasing and combination schemes send the on-axis light to specific outputs, leaving others free of this undesirable contribution. These so-called bright and dark outputs can be respectively discarded and analysed, as the later would carry spatial and spectral information on potential faint sources.

Just as the development of extreme adaptive optics systems has enabled the success of coronagraphs in observing exoplanets, the performance recently reached by fringe trackers should enable the performance of nulling beam combiners such as the coming Asgard/NOTT at the VLTI (Laugier et al. 2023), or potential LIFE space mission (Quanz et al. 2022; Dannert et al. 2022). While general purpose beam-combiners have been able to use the OIFITS data standard (Pauls et al. 2005; Duvert et al. 2017) for exchange and interpretation of observation data, the past and present nullers (Serabyn et al. 2012; Defrère et al. 2016; Norris et al. 2020) have

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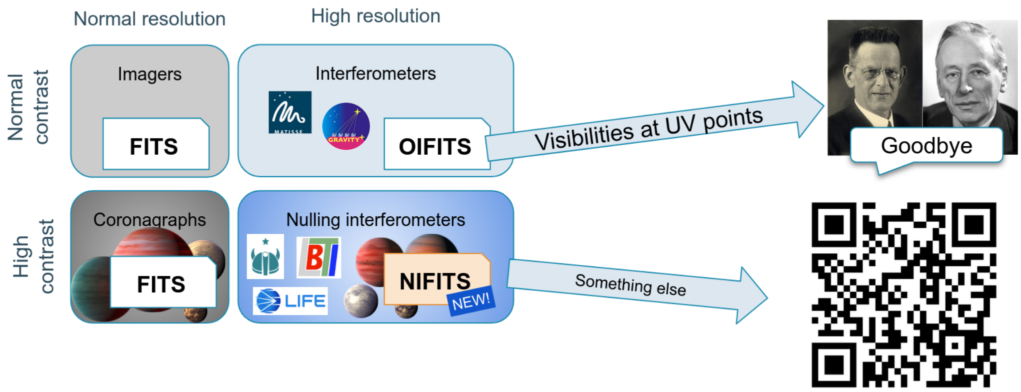

Fig. 1. OIFITS has enabled the exchange and interpretation of interferometry data. OIFITS implicitly relies on the Zernike and Van Cittert theorem which must be left behind for nulling beam-combiners.

been incompatible with OIFITS and their exploitation has remained a niche activity limited to the instrument team, leading to limited results. We propose a new data standard called NIFITS to fill this need and enable the interpretation of nulling interferometry data by researchers outside of the instrument team, without the need for expert knowledge of the instrument.

2 From OIFITS to NIFITS

Data interpretation tools such as PMOIRED(Mérand 2022), CANDID(Gallenne et al. 2015) OIMODELER (Juhasz et al. 2024), or even image reconstruction systems like MIRA(Thiébaut 2008) or SPARCO(Kluska et al. 2014) are meant to work with OIFITS which relies on the implicit use of the Zernike - Van Cittert (ZVC) theorem indicating that the visibilities, correlated fluxes or triple product thereof stored in the OIFITS file are to be matched with the Fourier transform of intensity distribution of the scene at spatial frequencies corresponding to the provided projected baseline and wavelength bin. This works because all classical beam-combiner produce and measure fringes occurring between pairs of apertures, therefore offering information relevant to that spatial frequency. As a result, the Fourier modes corresponding to the UV point samples are the relevant basis to express the data.

This consideration may remain relevant for Bracewell nullers, which combine a pair of telescopes offering one bright and one dark output measurements. However this type of beam-combiners has fallen out of consideration for most projects in favor of double-Bracewell or other staged combinations (Angel & Woolf 1997; Guyon et al. 2013; Martinache & Ireland 2018; Laugier et al. 2020; Hansen et al. 2022). In those configurations each output can be the phased combination of 3, 4 or more inputs. Their response in integrated flux to sources of light in the field of view has no particular shift-invariance. In the general cas, the use of Fourier modes to describe this response is not relevant. The nearest relevant approach would be to express it in the eigen-modes of the response of each particular instrument, and package the expression of these response modes in the files, along with the data, which is what NIFITS offers to do.

The NIFITS data standard offers a universal mathematical recipe that produces the transfer function of any nulling instrument, based solely on the metadata contained in the NIFITS files. Therefore the creator of the file (who will be assisted by the observing software developed by the instrument experts) can include this metadata along with the result of the observation. The user, who reads the file for interpretation can rely on NIFITS-compatible third-party software to be the forward-model in their model-fitting work, and can remain agnostic of the inner-workings of the instrument. The burden of expertise is bounded to the creator of the file.

With this logic, third-party NIFITS-compatible library are no longer tailor-made for a given instrument. They can be shared between teams and remain relevant beyond the lifecycle of a single instrument, making their improvement and maintenance worthwhile.

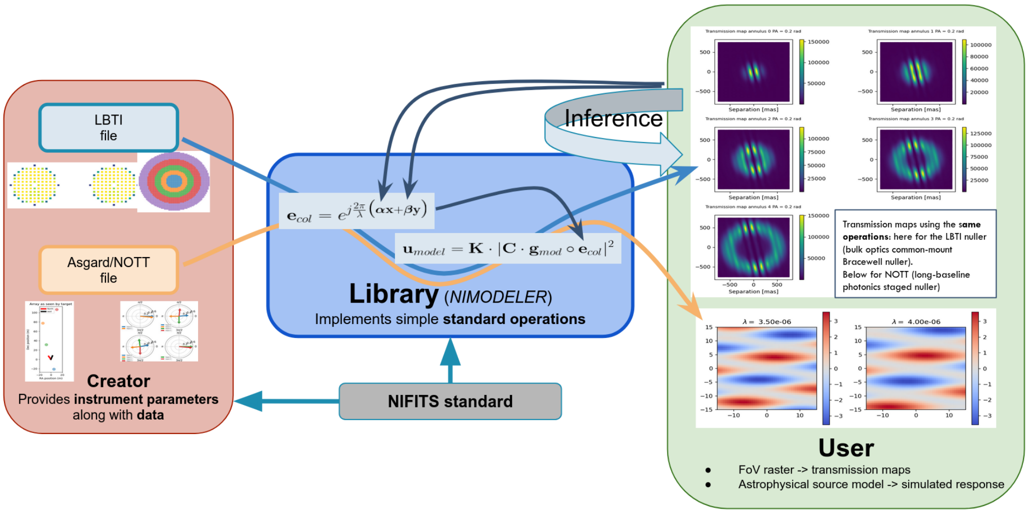

Fig. 2. A representation of the different roles of the NIFITS workflow. The creator of the file is the observer, assisted by the instrument tools and their data reduction library who are experts in the instrument. The standard defines how the files must be structured and what the information it contains means. It defines the mathematical operations that produce the instrument response function based on this data. This operation is typically done by third party softwares running their own implementation of an NIFITS-compatible backend (here called NIMODELER). The user uses this standard backend as their forward model to implement an inference loop for interpretation, without any expertise on the architecture of instrument that created the NIFITS file.

3 Principal constituants

A NIFITS file is a multi-extension FITS file, which may reuse some of the extensions relevant to OIFITS, such as an `OI_ARRAY`, an `OI_WAVELENGTH`, and `OI_TARGET` items. It may contain the data recorded from zero or more frames of observation, in tables such as `NI_IOUT` which records for each frame, the values collected at each of the outputs for each of the spectral channels in the specified units, such as count per second, or watts. It may also typically store a post-processing matrix to operate the linear combinations of output values as described by a kernel matrix stored in `NI_KMAT`.

The instrument model is included mainly as the `NI_CATM` which contains the complex amplitude transfer matrix, as popularized by Guyon et al. (2013) and Martinache & Ireland (2018) for each spectral channel of the instrument. The field of view function is described by a spatial filter defined by `NI_FOV`, while the `NI_MOD` describes how the light of each of the beams is filtered and phased for each of the frames of the observing sequence, before being sent to a dot-product with complex amplitude transfer matrix. The square modulus of the combiner outputs is then provided to the user, or its post-processing with a kernel matrix. A convariance matrix of the kernel output would then be included with a `NI_KCOV` extension.

This approach is expected to suffice to produce state-of-the-art forward model of any nuller known or envisioned, which should give the adequate longevity.

4 Discussions on the way forward

This poster presentation was meant to trigger conversations around this early concept for NIFITS, and to gather recommendations on how to construct a successful standard here are some main elements and our intentions to incorporate them.

The availability of tools matters: the OIFITS team means to offer the first NIFITS-compatible python library, including write and read functionality to the fits files, as well as a simple numerical backend implemented with numpy. This will be available on a github (`https://github.com/rlaugier/nifits`), which will also serve as a platform for documentation and exchanges around the standard itself.

Compatibility with OIFITS would be helpful: NIFITS is reusing some of the metadata extensions as much as possible. While the implementation had to change, NIFITS was meant to mimic OIFITS in its function.

Table 1. Summary of the NIFITS extensions

Extension	Required	Content
OI_ARRAY	metadata	Interferometer description for compatibility with OIFITS.
NI_MOD	data	Contains the time-varying information of the model, in particular the an interna modulation phasor vector, and the projected location of collecting apertures.
NI_CATM	metadata	The complex amplitude transfer matrix containing all static behavior of the system.
NI_KMAT	metadata	Identity is assumed if absent.
NI_IOUT	data	Contains the collected output flux.
NI_KIOUT	data	Contains post-processed output fluxes.
NI_KCOV	metadata	Expected covariance of the kernel data.
NI_OSAMP	metadata	Identity is assumed if absent.
NI_FOV	data	Contains the complex spatial filtering function.

Seek support from the JMMC: The NIFITS team is already in contact with the JMMC which has offered support in particular to provide file validation tools when the specifications have become stable.

Community is key: The NIFITS team includes member involved with several active and planned nullers (Asgard/NOTT, GLINT (Norris et al. 2020; Martinod et al. 2021), LIFE) and is well positioned to accompany the adoption of NIFITS by the community. In particular we will organize a hackathon where anyone interested can work on their own projects, for example to incorporate the backend to their own fitting tools, or implement the saving of NIFITS files by their own instruments or simulators. The organization of open data challenges (Cantalloube et al. 2022) is also planned, as it was one of the motivation for the creation of the standard.

5 Conclusion

Nulling interferometry may be the key to high-contrast discoveries at the smallest angular separations around stars, in particular in the infrared, where larger collector dimensions are needed. Their full scientific impact can only be obtained with the ability to share the observation results, which OIFITS is unable to provide. NIFITS fills this need by packaging a state-of-the-art forward model of the instrument along with the data which can be opened with any compatible third-party software without the need for instrument expertise.

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