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CHARACTERIZATION IN AN ERA OF NULLING INTERFEROMETRY: TOWARDS GROUND-BREAKING SPACE MISSIONS

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Abstract. High-contrast direct observations have been contributing to the long-period part of the exoplanet landscape. The advent of nullers such as Asgard/NOTT at VLTI, functioning as coronagraphs for interferometers, should unlock comparable performance at angular separations smaller by a factor 20, opening up resolved observations of giant planets at the snow line of young stars, and even hot Jupiters around nearby stars. In the coming twenty years, interferometry could complement reflected light observations from HWO with mid-infrared spectra of thermal emissions carrying crucial information of temperature, radii, and greenhouse effects in action. High-contrast imaging, whether with single dish coronagraphs or with long baseline with nulling interferometry, makes use of carefully designed and adjusted optics to set-aside the on-axis light of the star and prevent its contamination of the off-axis light present in its scientific channels. The leftovers of these operations constitute so-called leakage light and speckle residuals, which tend to dominate the error budget and are handled through post-processing. Both nulling and coronagraphic techniques face similar challenges of non-Gaussian distributed, correlated errors, and mixed multi-planet signals which are challenging at the post-processing level. We will present new innovative tools proposed by the nulling community to face and solve these challenges and emphasize some of the impact they have on the way we envision the interpretation of these results, not just for nullers, but also for coronagraphs. After describing some key aspects of Asgard/NOTT data interpretation, we will show how the control of this entire process is pivotal in the design of new generations of instruments, in particular in our effort to ensure the adequation of the instrument with its astrophysical ambitions. A discussion should then be had about what a data challenge could bring to this endeavor in the roadmap towards future ambitious space missions.

Keywords: exoplanets, characterization, direct detection, interferometry, high-contrast imaging

1 Introduction

High-contrast direct observations have been contributing to filling our discovery space for young giant planets at longer orbital periods. With the progress of wavefront control systems, coronagraphs aim to push this discovery space to shorter wavelengths, allowing for smaller inner working angles, and leading towards the NASA-led mission Habitable Worlds Observatory (HWO) (Stark et al. 2024). With this American mission targeting the peak of reflected light for temperate Earth-like worlds, there is another push led by European institutes called LIFE to target the thermal emission peak of such planets Quanz et al. (2022). Planetary science at such wavelengths ($6-18.5\mu$m) is extremely compelling and complementary, with much of carbon chemistry as well as the direct footprint of greenhouse effect in action, and a far more direct estimation of atmospheric temperature. But with wavelengths longer by a factor 10 or more, such a mission requires physical collector dimensions larger in the same proportion. This directly prompts the use of interferometry, where nulling beam-combiners can take the role of high-contrast instruments.

On shorter time scales, Asgard/NOTT Defrère et al. (2024)is planned to reach the sky in 2026 and to be the first interferometric nuller at the VLTI and the first four-telescope nuller. It will also be the first nuller in

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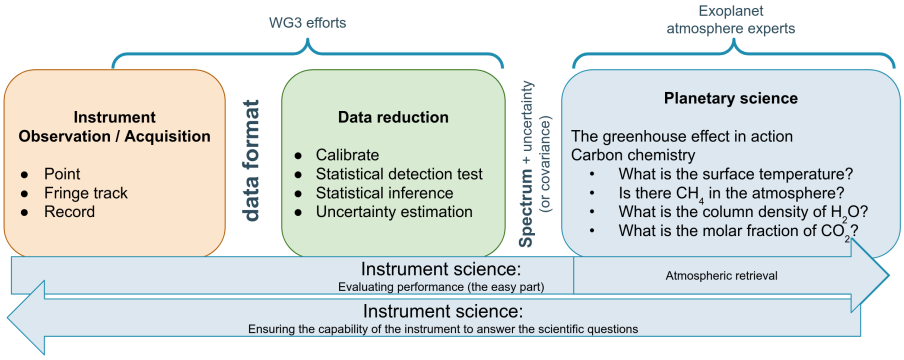

Fig. 1. The classical observational investigation of exoplanet science. The role of instrument science is represented by the bottom arrows: from left to right the evaluation of the instrument performance in a given configuration, and from right to left, the more challenging construction of instrumental requirement from a set of top-level scientific goals.

the southern hemisphere, and the first to operate in the L band, where the contrast is most favorable for young giant planets. As such, it will open for high-contrast imaging an unprecedented angular resolution, down to $3-5$mas. Here we describe some lessons learned in instrument science and data reduction in this transition era from ground, to space-based nulling interferometry.

It is worth reminding that astrophysical observations in general are not meant to produce images. Instead, and as the medieval mathematician al-Khwarizmi underlined, what people want is usually a number. In our case, this is traditionally the relative astrometric position of the planet, its photometry, and its spectrum. In truth, with the current maturity of exoplanet science, one must consider that the answers sought are rather the surface temperature, the pressure-temperature profile of planetary atmosphere and volume mixing ratio of its constituting molecules Alei et al. (2024). In Figure 1, we identify three steps: i) the observation, ii) the data reduction, and iii) the planetary science often called atmospheric recovery.

The accepted approach to this first step is common to any observations and is described in Figure 2. An observation is made of the real "ground truth" target through an instrument which gives an output and saved to a *fits* file. This may include some form of actual reduction (binning, coadding, averaging or other). The role of the user is to construct a parametric model of the system, and use an instrument model to produce model outputs (so-called observables) that can be compared to the recorded outputs of the observation. This comparison, which uses a form of cost function, can drive the adjustment of the model parameters, towards values that become the numerical answer to our question.

With coronagraphs, the instrument function is often considered trivial as pixel position can be associated to a relative sky position. Refinements of this model can be layered, including an instrumental PSF from the diffraction, the more complicated coronagraph transmission function, and possibly the effect of speckles coming from imperfect wavefront. With classical long baseline optical interferometry, the model is radically different but it is a direct interpretation of the Zernike van Cittert theorem stating that the measured (complex) visibility measured from the recombination of each pair of telescopes is to be compared to the Fourier transform of the intensity distribution of the scene sampled at the spatial frequencies corresponding to the projected baseline of that telescope pair. This is true for all traditional interferometers that all measure the fringes more or less independently for each pair of telescopes.

2 NIFITS to bridge the data gap

However, nulling beam-combiners do not produce such a measurement of complex visibility, pushing us outside of the applicability of this theorem. This shift is demanded to obtain flux measurements from the vicinity of a star while avoiding the photon noise of this bright central source (paper in prep.) . The light-gathering capability of the so-called dark outputs is described by instrument transmission function often showed as transmission maps (Lagadec et al. 2018). They depend not-only on the beam-combiner, but also on the adjustment of the input beam phasing, or modulation thereof. The new format recently proposed called NIFITS packages all of this information and provide them unambiguously to the user so that they can form their inference.

Through the efforts of the instrument science teams of Asgard/NOTT and LIFE, we have pushed, consolidated and improved the workflows of interpretation, in particular to enable a thorough evaluation of perfor-

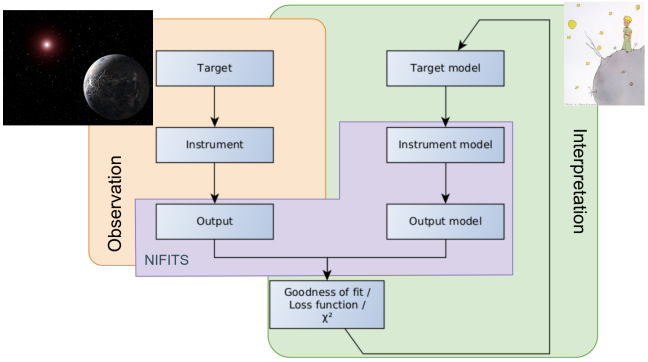

Fig. 2. The traditional statistical inference (also called model fitting). The role of the NIFITS is highlighted in mauve and allows an agnostic user to make use the arbitrary instrument forward model of any instrument using the standard.

mance. We can now evaluate sensitivity of planet detection accounting different levels of correlated instrumental noise (Rutten et al. 2025 in prep.). We can also evaluate the covariance obtained on the spectrum of a planet depending of observing conditions. Furthermore Dannert et al. (2025) has obtained results on a semi-analytical model of the instrumental systematic errors distribution and its impact on the test statistics, offering some compensation parameters, and we have deployed algorithms to account for the covariance in nulling data, both for Asgard/NOTT (Laugier et al. 2023) and for LIFE Huber et al. (2025), and draw conclusions for the final performance. Furthermore, the risk of one given LIFE configuration to lead to the confusion of multiple planets has been quantified by Cacaj et al. (2025).

One of the challenges in instrument science is not only to obtain this performance function, but also to invert it. That is given the requirements on the precision of a measurement, to obtain the instrumental parameters and characteristics that will enable them. In this context, the existence of standardized workflows and instrument definitions allow to invest efforts in the deployment of the complex tools to do that.

3 Bridging the interpretation gap

Although it involves different types of models, the step of atmospheric recovery is similar. Here the parameters are those of atmospheric temperature, pressure, and chemistry. They are coupled to a radiative transfer model that simulates the propagation of radiation through the layers of the atmosphere, leading to the observable which is here a spectrum. The goodness of fit, or cost function, is obtained by comparison of this spectrum with the spectrum obtained through the reduction inference in the previous step.

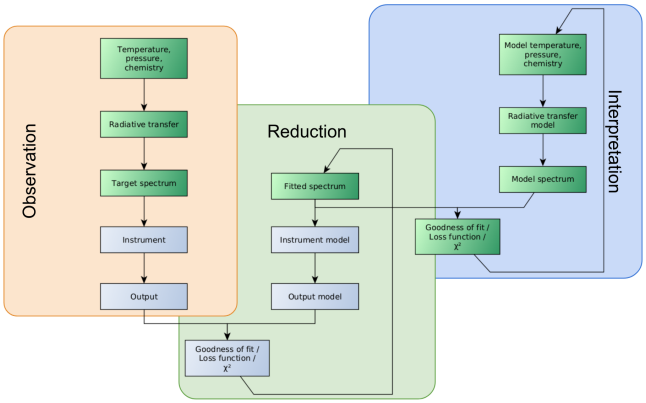

Fig. 3. A schematic representation that expands Fig. 2 and including the interpretation of a spectrum in terms through another inference loop (in blue) called atmospheric retrieval. The whole process is the result of a double inference loop which makes challenging to converge on instrumental requirements. A single-loop process bypassing a planet spectrum may help in this regard.

As illustrated by Figure 3, the whole process is therefore made up of two inference loops in series. This means a layered complexity within the task of instrument science to express the performance of a given observing scenario, and even more for the inverse task of producing the instrumental requirement from the top-level science goals. The recent progress accomplished thanks to NIFITS for bridging the first gap has shown that the spectrum that is passed from reduction to atmospheric recovery comes with a covariance matrix with off-diagonal terms that can be structured and may be non-negligible in certain observing scenarios Huber et al. (2025). This extracted covariance may also involve the spectra of the different planets of the system.

Propagating the science requirements through the terms of such covariance matrices to reach instrumental requirements would be extremely complicated. A solution would be to skip the step of the inference on spectrum and consider a single inference process, from the raw observables to the atmospheric parameters. Such an approach may now be considered thanks to the way NIFITS operates and may help to converge faster on instrumental requirements. In any case, the organization of a form of fiducial cases mapping the anticipated science cases is necessary to navigate the construction of solid instrumental requirements. The construction of a data challenge may also be a very effective way to promote the investigation of this complicated relationship.

4 Conclusion

Nulling interferometry allows the extension of coronagraphs beyond the angular resolution of single telescopes by applying similar methods to the recombination of interferometric arrays. The interpretation of nulling data has been challenging due to the diversity of nuller architectures. The new data format NIFITS solves this problem by facilitating the exchange of standardized instrument forward model, a practice which also facilitates efforts in instrument science.

The results mentioned here are only the first successes in the complicated plan to develop a space interferometer tailor-made for the study of the carbon chemistry and the greenhouse effect in action in the atmosphere of temperate earth-like planets. We have put together the tools to properly handle the different complexities related to such ground-breaking interferometric observations, but further inputs and tighter collaborations are needed with the community of exo-atmosphere science to formalize scientific goals that can more effectively drive the technical decisions for such an ambitious mission. Tighter collaborations between nulling interferometry and coronagraphy communities is highly advisable as the methods share important commonalities in their physical principles of operation, and as a result face a number of common challenges.

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