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WHITE PAPER FOR EXO-PLANET ROADMAP ADVISORY TEAM

TECHNOLOGICAL STATUS AND ROADMAP FOR NULLING INTERFEROMETRY

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ABSTRACT

This White Paper aims at contributing to the technological development roadmap of nulling interferometry, by:

1. summarising the already performed technological achievements
2. identifying the remaining challenges
3. proposing a development logic.

Today the following major challenges have been met:

1. Deep nulling in line with mission's needs, in wideband natural light conditions, was demonstrated in the US in the mission's spectral range. Similar NIR demonstrations have been performed in Europe
2. Stability of the order of mission's needs was demonstrated in both the US and in Europe
3. Technological solutions for all the elementary functions, including the modal filter, have been identified and tested over at least a substantial fraction of the mission's spectral range, with encouraging perspectives of covering the whole band.

From that point, our proposed development logic is based on the following rationale: in a first step, all elementary technological developments should be completed, and the basic architecture of the interferometer should be decided and its validity demonstrated. This first step should remain as cost-effective as possible until all possible issues related to feasibility are cleared. In particular tests should remain in conventional lab environment.

Then a demonstration of the essential performance should be performed. In particular, nulling depth/stability and radiometric efficiency should be demonstrated over the entire spectral range.

The success of this step will open the door to the development of a complete instrumental mockup and the demonstration of the end-to end performance in the laboratory.

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1. INTRODUCTION

Nulling interferometry in the thermal infrared represents one of the most attractive candidate techniques for the direct observation of exo-Earths. Due to its sensitivity, this innovative technique requires a number of challenging high-performance functions and real-time controls.

A number of activities have been put in place on both sides of the Atlantic, mostly on the initiative of ESA and NASA, in order to meet these challenges. They have recently led to considerable progress in the performance and stability of the demonstration breadboards. Many important challenges have already been met, while many others remain. This White Paper aims at contributing to the technological development roadmap of nulling interferometry, by:

4. summarising the already performed technological achievements
5. identifying the remaining challenges
6. proposing a development logic.

Note that this White Paper focuses on the interferometry payload and does not address the issue of Formation Flying technology.

2. REFERENCE DOCUMENTS - BIBLIOGRAPHY

RD1. Lay O.P, "Systematic errors in nulling interferometers", Applied Optics, 43, 6100-6123, 2004

RD2. Lawson P. R., Lay O. P., Martin S. R., Peters R. D., Gappinger R. O., Ksendzov A., Scharf D. P., Beichman C. A., Johnston K. J., Danchi W. C., Serabyn E., Terrestrial planet finder interferometer: 2007-2008 progress and plans, Proceedings of SPIE Vol. 7013, 701394 (2008)

RD3. Booth A. J., Martin S. R., Terrestrial planet finder, planet detection test-bed: latest results of planet light detection in the presence of starlight, Proceedings of SPIE Vol. 7013, 701371 (2008)

RD4. Buisset C., Rejeaunier X., Rabbia Y. and Barillot M., "Stable deep nulling in polychromatic unpolarized light with multiaxial beam combination", App. Opt. 46, 32, 7817-7822 (2007).

RD5. Peters R. D., Lay O. P., and Jeganathan M., Broadband phase and intensity compensation with a deformable mirror for an interferometric nuller, App. Opt. 47, 21, 3920 (2008)

RD6. Peters R. D. and Lay O. P., Progress in deep broadband interferometric nulling with the adaptive nuller, Proceedings of SPIE Vol. 7013, 701366 (2008)

RD7. Serabyn E., First deep nulling science observations with the Keck interferometer nuller, Proceedings of SPIE Vol. 7013, 701365 (2008)

RD8. Gabor P., Chazelas B., Brachet F., Decaudin M., Jacquinod S., Labeque A., Leger A. M., Dithering as an approach in stabilizing nulling interferometers, , Proceedings of SPIE Vol. 7013, 7013173 (2008)

RD9. Le Duigou J.-M., Cassaing F., Houairi K., Jacquinod S., Reess J.-M., Hénault F., Sorrente B., Barillot M., Mourard D., Coudé du Foresto V., Ollivier M., PERSEE: A nulling breadboard coupled with a free flying GNC simulator, 3rd Int. Symposium on Formation Flying, Missions and Technologies, Noordwijk (2008)

RD10. Lewi T., Ksendzov A., Martin S. R., Lay O. P., Shalem S., Tsun A., Katzir A., Lawson P. R., Silver halide single mode fibers for modal filtering in the middle infrared, Proceedings of SPIE Vol. 7013, 701337 (2008)

RD11. Barillot M., Barthelemy E., Broquin J. E., Frayret J., Grelin J., Hawkins G., Kirschner V., Parent G., Pradel A., Rossi E., Vigreux C., Zhang S. Q., Zhang X. H., Integrated optics for nulling interferometry in the thermal infrared, Proceedings of SPIE Vol. 7013, 701338 (2008)

RD12. Danto S., Houizot P., Boussard-Pledel C., Zhang X. H., Smektala F. and Lucas J., "A family of far infrared transmitting glasses in the GaGeTe system for space applications", Adv. Funct. Mater. 16, 14, 1847-52 (2006).

RD13. Serabyn E., Colavita M., "Fully symmetric nulling beam combiners", App. Opt. 40, 10, 1668-1671 (2001).

RD14. Weber V., Barillot M., Haguenauer P., Kern P., Schanen-Duport I., Labeye P., Pujol L. and Sodnik Z., "Nulling interferometer based on an Integrated Optics combiner", Proceedings of SPIE Vol. 5491, pp. 842-850 (2004).

3. MAIN CHALLENGES OF NULLING INTERFEROMETRY FOR THE DIRECT OBSERVATION OF EXOPLANETS

3.1 Performance challenges

3.1.1 Spectral range

Detection of life in the thermal infrared requires a typical [6-20µm] spectral range.

In space optics, significant technological experience exists in the [6-15µm] spectral range, where practical materials and detectors are widely operated.

However, the 15µm to 20µm requires the use of more innovative or unpractical materials and more sophisticated detectors. Furthermore, performing experimental nulling above 12µm in the laboratory certainly requires a cryo-vacuum environment for radiometric efficiency reasons (weak sources, strong background, CO2 absorption).

A second issue concerns the possible splitting of the spectral band into two or more sub-bands, with potential strong impact on instrument architecture.

3.1.2 Nulling efficiency

Detection of life in the thermal infrared requires a typical (~105) nulling over the whole spectral range. In order to achieve this performance a remarkable control of the instrument must be performed. In particular (orders of magnitude are given for simplicity):

- Optical path differences must be controlled to typically 1/1000 of a wavelength.
- A spectrally uniform phase shift must be applied between the interferometer arms, to accuracies of the order of typically 1/1000 of a wavelength.
- Wavefront differences between interfering arms must not exceed typically 1/1000 of a wavelength, which requires single-mode waveguide as "modal" WFE filter.
- Interfering intensities must be balanced to an accuracy of 10-2 to 10-3.
- Differential polarisation must be kept below typically 1/1000 of a wavelength (birefringence) and 1mrad (rotation).

3.1.3 Radiometric efficiency

The need for strong radiometric efficiency is obvious when one considers the flux received from an Earth-like planet at a 10-100 light-years distance. This generates a need to reduce the loss of light power to a bare minimum, which rises the performance challenges at nearly every technological level.

3.2 Operational challenges

3.2.1 Interferometer configuration and architecture

The selection of the most appropriate instrumental concept (number of telescopes, geometry...) is driven by both the performance and cost of the mission. In turn, the instrumental concept drives the architecture of the nulling interferometer.

3.2.2 Stability

Due to the extreme faintness of the observed objects, very long integration times are necessary: a typical 20mn accumulation is necessary for each raw data element. All the performance challenges described earlier must be met and kept extremely stable during the complete integration time.

On top of that, the need to modulate the signal to discriminate signal from noises and the number of potential targets in the sky generate long overall observation times and call for a very high duty cycle or availability.

3.2.3 Signal post-processing

Demodulation of the signal is not sufficient to retrieve the scientific data. False planet detection may be generated by spurious phenomena such as the so-called "instability noise" [RD1], which cannot be entirely removed by conventional calibration/demodulation processes. Efficient post processing would be a great help to mitigate the otherwise extremely stringent requirements on the instrumental stability.

3.3 Functional challenges

Most of the elementary functions of the interferometer show challenging features (Table 1)

Function	Critical driver
Collecting telescopes	Mass, cost, Radiometric efficiency
Optical components/technology: reflective materials, refractive materials, anti-reflective solutions, beam-splitters, dichroics…	Spectral range, Radiometric efficiency, Nulling efficiency (polarisation)
Achromatic Phase-Shifter	Nulling efficiency (dispersion, polarisation), possibly spectral range
Fringe and Wavefront Sensor	Stability, Nulling efficiency
Optical Delay Line	Stability, Nulling efficiency
Wavefront and/or tip-tilt corrector	Stability, Radiometric efficiency
Beam combiner	Nulling efficiency, Radiometric efficiency, spectral range
Modal filter	Spectral range, Radiometric efficiency, Nulling efficiency
Detectors	Spectral range, Radiometric efficiency

Table 1: Challenges of Nulling interferometry functions

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4. ALREADY PERFORMED TECHNOLOGICAL ACHIEVEMENTS

4.1 Interferometer configuration

For one year **a worldwide consensus has been emerging in favour of the "Emma X-Array" configuration [RD2]**. In this context the Emma X-array configuration should be taken into account when it drives the architecture and technological developments, e.g. at beam combiner level.

X-array interferometry was successfully demonstrated by JPL in the lab, within the mission's spectral band [RD3]. This very encouraging result opens the door to a next step: the preparation of a new lab arrangement, more representative of a flight instrument.

A good point about the X-array configuration is that since it is based on a first stage of two identical 2-beam nulling interferometers. Therefore most experimental nulling investigations, which involve 2 beams for simplicity, are relevant.

4.2 Nulling

Nulling was the subject of considerable investigations in the last 10 years. Several teams already managed to reach stable, reproducible and deep enough (~105) nulling in natural (i.e. non monochromatic, non-polarised) light. In Europe, see [RD4]. Moreover, **JPL teams recently succeeded in the demonstration of deep nulling in the [8-12µm] spectral range, a very significant achievement [RD5,6]**. JPL also operated a nulling instrument on the sky [RD7].

4.3 Spectral range

Spectral range issues are manifold. At elementary technologies level, the situation is highly variable and is summarised in Table 2. At interferometer level, experimental verifications were up to now focussed on Near Infra-Red (NIR) or [8-12µm] for practical reasons.

For memory, preliminary investigations on innovative materials and anti-reflective solutions to be used in the [15-20µm] range were started in the framework of the Achromatic Phase-shifter (APS) and Integrated Optics (IO) activities.

4.4 Radiometric efficiency

Up to now no activity was focussed at improving radiometric efficiency only. Clearly demonstrating the feasibility of the nulling performance and stability were considered priority one.

4.5 Stability

The first long term demonstration of stable deep nulling is to be credited to a European team in 2007 [RD4]. Since then JPL teams also reached comparable performance levels [RD3, 6] and novel techniques were developed and demonstrated to enhance long term stability [RD8].

A remarkable point is that the long term stability results were obtained in relatively conventional environment: ambient temperature, ambient pressure (hence turbulence), conventional optical tables and no special protection from acoustic noise (except conventional laboratory covers), conventional close-loop controls.

Despite these unstable environmental conditions the typical stability of the lab nulling interferometers reaches a few nanometers rms, virtually in line with the mission needs.

The on-going development of the PERSEE interferometer by CNES [RD9] also deserves to be mentioned since it aims at demonstrating the overall stability of a nulling interferometer, including the simulation of the perturbations of the instrument generated by Formation Flying.

4.6 Post-processing

Developments of post-processing algorithms are on-going in the framework of ESA's RESSP activity. Conclusions regarding the performance and robustness are expected in 2008.

4.7 Interferometer functions

Function	Demonstration status	ESA activity
Collecting telescopes	Small size prototype in preparation	ULT
Optical components/technology:	Partial: COTS solutions within 15µm ; consolidation needed bw. 15 and 20µm	POCI (Intended)
Achromatic Phase-Shifter	OK (numerical) over whole spectrum	MAII, APS
Fringe and Wavefront Sensor	OK at conceptual prototype level	DWARF
Optical Delay Line	OK at prototype level	ODL
Wavefront/tip-tilt corrector	Partial ; heritage from astronomy	
Beam combiner	OK several solutions successfully tried	MAII, EVMI, IODA, IO
Modal filter	Functionally OK in the [8-12µm] range.	FOWF, SMF, SMW, IODA, IO
Detectors	OK in the US, partial in Europe	FIRLA, BIBDRE

Table 2: In the past years significant progress occurred over the whole range of nulling interferometer functions and components

4.8 Synthesis of the major achievements to date

Today the following major challenges have been met:

4. Deep nulling in line with mission's needs, in wideband natural light conditions, was demonstrated in the US in the mission's spectral range. Similar NIR demonstrations have been performed in Europe
5. Stability of the order of mission's needs was demonstrated in both the US and in Europe
6. Technological solutions for all the elementary functions, including the modal filter, have been identified and tested over at least a substantial fraction of the mission's spectral range, with encouraging perspectives of covering the whole band.

It can be considered that the preliminary investigation effort is now completed. Several teams now have significant command of the technique.

5. REMAINING CHALLENGES

5.1 Modal filtering

Among elementary technologies, modal filtering remains the most critical issue, since no solution exists yet in the whole spectral range. However, the **recent progress of silver halide fibres [RD10], chalcogenide fibres and chalcogenide integrated optics [RD11] has provided very encouraging results which give the indication that the emergence of one or more solutions to this issue is now very likely within a couple of years typically.**

5.2 Spectral range, radiometric efficiency and optical components

Extension of the spectral range of the components to the complete spectrum of the mission is a mandatory step. The issue lies in optimising the transmission efficiency up to the longer wavelengths, for every necessary technology: reflective and refractive materials, coatings… For these reason the three topics are tightly connected to each other.

Nevertheless the issue enjoys a more advanced status than modal filtering: the open questions lies at the level of the selection and improvement of the most appropriate solution and/or materials (see e.g. [RD12]) rather than at the feasibility level.

5.3 Interferometer architecture

First, selection should be made of the most appropriate solutions at functional level: which achromatic phase shifter ? Which beam combiner ? Which internal metrology ? For example, deep nulling demonstrations were already achieved by means of bulk symmetric interferometers [RD13], multi-axial beam combination into a fibre [RD4], and integrated optics solutions [RD14].

Second, the selected solutions must have an architecture compatible with the mission needs (X-array) and with space implementation. A pertinent trade-off should take into account not only the potential performance, but also the experimental behaviour and the future constraints of the space instrument.

5.4 Stability

Stability demonstrations should take into account the perturbations which the instrument will have to face in-flight and not only the perturbations generated by the lab environment, in the spirit of the PERSEE project. Furthermore the compatibility between residual instability and the filtering power of the post-processing should be investigated.

5.5 Post-processing

The already started efforts need to be continued at least until the post processing capability to filter instability noise is assessed.

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6. DEVELOPMENT LOGIC

Our proposed development logic is based on the following rationale: in a first step, all elementary technological developments should be completed, and the basic architecture of the interferometer should be decided and its validity demonstrated. This first step should remain as cost-effective as possible until all possible issues related to feasibility are cleared.

Then a demonstration of the essential performance should be performed. In particular, nulling depth/stability and radiometric efficiency should be demonstrated over the entire spectral range. The success of this step will open the door to the development of a complete instrumental mockup and the demonstration of the end-to end performance in the laboratory.

6.1 Step 1: cost-effective consolidation of the feasibility and performance

All Step1 activities can be performed in conventional laboratory environment, as demonstrated by the past US results, and can be performed in parallel.

6.1.1 Step 1a: consolidation of the building blocks

The following technological development should be completed: modal filters, optical components, detectors and post-processing (incl. validation of mitigation of instability noise).

6.1.2 Step 1b: preparation of the nulling demonstrations in conventional lab conditions

A 2-beam nulling demonstration in the 8-12µm range should be made and should include a trade-off on the main functions (beam-combiner, APS, etc…) including experimental tests.

In parallel a realistic X-array demonstrator should be prepared in view of a preliminary proof of instrumental stability and mitigation of instability noise by coupling with a post-processing prototype. "Realistic" means that the design of this demonstrator should take into account: the future space application, in that it should be made as simple, compact and robust as possible.

6.2 Step 2: Stable nulling demonstration in each spectral sub-band

Upgrade of the 2-beam nuller of step 1 with the new LWIR components and demonstration of nulling over each of the spectral sub-bands. Spectral subbands will have to be relevant with respect to a space implementation. This demonstration will have to be achieved in cryo vacuum environment ; therefore the activity should be preceded by the adaptation of the interferometer functions wherever necessary.

6.3 Step 3: end-to-end demonstration of an instrument representative breadboard.

Development of a complete interferometer, capable of meeting the performance throughout the whole spectrum and including the injection of perturbations by means of coupling with a GNC simulator.

This interferometer should be reasonably flight representative.

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