White Paper

in response to the call from

ESA's Exo-Planet Roadmap Advisory Team (EPR-AT)

on

Methods, Technologies and Roadmaps towards Exo-Planet Detection and Characterization from a Prime Contractor's View

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1 Introduction

Over the past years, ASTRIUM has undertaken numerous technology development activities and mission definition studies for ESA and for national customers in Germany and France in the context of exo-planet detection and characterization. These activities have been additionally prepared and supported by substantial company internal R&D activities.

This white paper provides in chapter 2 a prime contractor's view on the potential and technical status of the various techniques and systems under discussion for exo-planet detection and characterization in space.

In chapter 3 we briefly sketch detailed technology development plans submitted to ESA on cryogenic nulling demonstration and formation flying ground testing. These plans have been initially worked out within company R&D activities and have been later refined in the course of ESA studies (appropriate references are provided).

Finally in chapter 4 we stress the role of pre-competitive development activities in order to arrive at a consistent mission architecture and technology development plan between ESA and competitive industrial partners.

2 Assessment of methods and techniques

2.1 Principal observation methods

The principal observation methods for exo-planet detection -and in some cases characterization- are:

- Transit detection: photometry and spectroscopy
- Microlensing
- Astrometry
- Radial velocity / Doppler effect
- Coronagraphy
- Mid-infrared nulling interferometry
- External occultation

Those methods have to be matched to the different science mission classes ESA now has introduced in the frame of the Cosmic Vision 2015-25 process (medium, large, and long term goals).

2.2 Transit detection, photometry and spectroscopy

Precision photometry measures in the visible spectrum the dips in stellar luminosity in case of planetary transits. In preparing the PLATO mission assessment study, ASTRIUM analyzed the required technologies, identifying as key:

- High stability optical instrumentation
- High stability spacecraft pointing
- (Visible) detector technology, low noise, radiation tolerant, long term stability, calibration
- Onboard data processing for handling of high data volume

As these technologies are key not only for photometry missions, a high level of technological maturity from other science (e.g. GAIA) and earth observation missions is available, making a photometry mission directly feasible with state-of-the-art technologies and minor delta developments.

For spectroscopy, SPITZER recently provided spectroscopic measurements in the Mid-IR of hot Jupiter atmospheres at secondary (planet behind star) and primary (in front) eclipses. The necessary infrared detector technology has been studied in detail by ASTRIUM for MIRI and DARWIN, and MIRI is now being built under ASTRIUM industrial lead. For a cryogenic telescope, the SPICA telescope design studies by ASTRIUM proved the feasibility of European SiC technology for ~4K cryogenic mirrors & telescopes.

2.3 Microlensing

Several exo-planets have been detected by microlensing effects on background stars through the ground-based OGLE survey. For this sort of survey a high stellar density on sky is required, clearly preferring the direction to the central bulge of our galaxy. In the US a space microlensing mission has been proposed (GEST).

From a technology perspective the key technologies for microlensing are similar to those of a photometry mission, with high technological readiness, too. So the decision between photometry and microlensing missions has to be taken from a science perspective, as the two methods account for different samples of stars and different follow-up observations.

Microlensing is a single event for a given exo-planet and confirmations require astrometry or radial velocity measurements. As co-alignment with the lensed background star is principally given, a follow-up observation with a exo-planet characterization mission (nulling, coronagraphy) is difficult, but the method microlensing in itself allows principally for detections of exo-planet with earth-like masses.

2.4 Astrometry

Astrometry allows exo-planet detection by measuring lateral periodic displacements of the parent star. ASTRIUM is prime for the GAIA mission, the GAIA service module and the GAIA optical payload.

The GAIA working principle is based on precise centroiding of stars, providing a survey of the full sky. In the US, the SIM mission (currently on hold) follows an interferometric measurement principle, focussing on very precise position measurements of selected individual stars.

ASTRIUM has undertaken phase-A studies on such interferometric astrometric measurements (complementary to GAIA) for the PRIMA Phase Referencing IMaging and Astrometry instrument for ESO VLTI. In some sense this is the European ground-based equivalent to the NASA SIM mission.

For SIM-like missions, one of the key technologies is stability and control of the interferometric baseline and telescope orientation to the picometer level. For picometer metrology and picometer stability, ASTRIUM has a broad technology heritage from LISA and LISA test package optical benches (now in proto-flight model status).

2.5 Radial velocity

Radial velocity measurements are up to now only undertaken from ground and are currently benefiting from major advantages in spectral calibration as e.g. by the forthcoming use of optical frequency combs. As the atmosphere poses no major limitations to this measurement principle, space missions for radial velocity measurements are therefore not expected.

2.6 Coronagraphy

Though no European assessment study on a stellar coronagraphy mission has been conducted up to now, the status and progress of the NASA TPF-C mission and the respective testbeds have been closely monitored in the context of company internal R&D activities at ASTRIUM.

Star suppression

About 20 different star suppression coronagraph techniques are under discussion, with various breadboards at different institutions. The challenge in selecting one of those consists in carefully balancing performance, inner working angle and contrast with manufacturability and resulting system complexity.

This multitude of concepts cannot be traded “on paper” solely and therefore a diversity of breadboards is in work, mostly in the US and to some extent in Japan/Subaru telescope. Currently industry cannot decide and select one concept based on the momentarily available experimental results, therefore we would recommend first to conduct a European “strawman” design study on one of the star suppression concepts, focussing on the payload. The Phase Induced Amplitude Apodizer PIAA is a good candidate as the method claims a good combination of transmission efficiency, angular resolution, achromaticity and modest alignment sensitivities, and therefore is favoured by several parties in the US.

Wavefront sensing and correction

Active wavefront correction down to ~50 pm RMS has never been studied in Europe for space applications. Clearly this technology branch is driven by extreme adaptive optics developments for next generation instrumentations on VLT and LBT for atmospheric correction, though for residual wavefront errors orders of magnitude above.

Longterm stability measurements on the ~50 pm level for closed loop wavefront control have never been demonstrated and require a dedicated technology development activity.

2.7 Mid-infrared nulling interferometry

Here ASTRIUM has extensively contributed in the last eight years to ESA mission assessment studies and the technology & research program on nulling interferometers, formation flying, science and system performance, cryogenic test setups etc. The latest mission status summary has been provided in December 2006 to ESA within the technical data package to ESA contract 19333/05/NL/HB “DARWIN system assessment study” and by a follow-on technical note TN8 on mission consolidation in July 2007. Therein detailed propositions and recommendations to a nulling interferometry technology development plan are provided, as well as all essential system and performance budget breakdowns. A short overview of the development plans is provided in chapter 3.

Two mission assessment studies have been conducted in 2005-2007 in a competitive way by two industry consortia, resulting in two quite different mission baselines in terms of array geometry (planar-nonplanar), array configuration (TTN vs X-array) and beam combination (pupil vs image plane). In a potential next series of technology development activities these different mission baselines would lead to differing and sometimes contradicting requirements for several key subsystems. Therefore a mission baseline consolidation is recommended prior to new development activities, and ASTRIUM offers its support based on previous study results and insights.

After July 2007, the Cosmic Vision 2015-25 down-selection process put on hold practically all technology development activities for nulling interferometry in Europe, except a near-infared breadboard for the PERSEE mission and the mid-IR single mode fiber development (ASTRIUM & TNO). Beyond this, progress in the Mid-IR nulling has been achieved in the US in terms of successful breadboard tests with the so-called "Adaptive Nuller". The promising results indicate that optical tolerancing for nulling interferometry can be significantly relaxed, given that a corrective element (the adaptive nuller) is included that allows for active correction of differential dispersion and polarization of the individual optical beam trains.

Finally we provide a short list of the TRP activities on nulling interferometry where ASTRIUM has participated and built up company know-how which can be drawn on in next steps. ASTRIUM is undertaking internal activities to keep this knowledge together.

List of TRP activities undertaken at ASTRIUM

- Nulling interferometer testbed at ambient temperature
- Single mode fiber for DARWIN 1&2
- FINCH DARWIN optodynamic end-to-end simulator
- GENIE design study for ground-based nulling demonstration and operation (&exozodi characterization)
- ICD&ICC for interferometer constellation deployment and control
- Formation Flying definition studies for Formation Flying Ground TestBed FFGTB, PROBA-3, & SIMBOL-X
- High precision optical metrology HPOM 1&2
- Fiber optical wavefront filtering 1&2
- Cryogenic optical delay line for DARWIN
- Assessment of cryogenic coolers for mid-IR detectors, selecting a European sorption cooler. Development of cooler simulation and systems engineering tools under internal R&D.

2.8 External occulters, also in combination with coronagraphs

The reference mission design for an external occulter is the "New World Observer" mission studied in the US, providing directly a contrast of the required 10^{-10}. This relies on a very complex occulter shape to beat diffraction at the edges and an inter-spacecraft distance of some ten-thousand kilometers for L2 orbits. To date no independent assessment has been conducted by ASTRIUM internally.

ASTRIUM has all key competences available, for mission analysis as well as for sophisticated optical diffraction calculations using Fresnel diffraction propagators. Recently designs were proposed in the coronagraphy community that combine modest contrast external occulters with modest contrast coronagraphs to achieve together the 10^{-10} contrast required in the visible.

3 Technology development plans and system modelling

3.1 Nulling testbed development plan

A detailed development plan has been provided in TN8 of ESA contract 19333/05/NL/HB "DARWIN system assessment study". The plan foresees to start with a mid-infrared Bracewell beam combiner core (step 1) and to subsequently add single-mode fibers (step 2, after completion of currently running development studies), active control with delay lines (3), periscopes (4), and finally residual error compensation (5, or nowadays the US adaptive nuller). Initially the work can be done at ambient temperature with several mid-infrared laser sources plus a thermal source up to ~ 12µm, but eventually has to go into cryogenic environment.

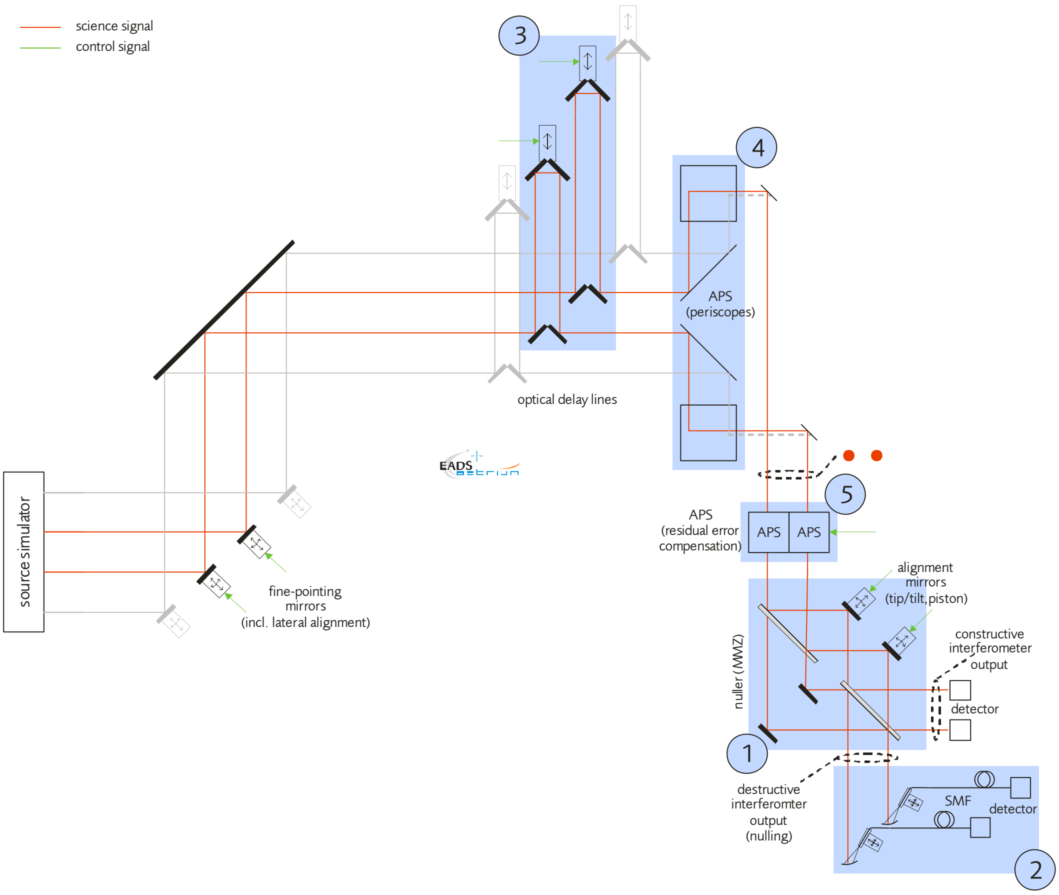

Fig. 3.1-1 Generic setup of the gradually expanded two beam nulling testbed for subsystem performance verification. (The individual steps are indicated.)

These testbeds are universal in the sense that they are relevant for each nulling interferometry mission, given that pupil plane beam combination is selected. ASTRIUM offers to discuss more precise definitions of such testbeds in the context of establishing a exo-planet technology development roadmap.

3.2 Formation flying technology demonstration

On-ground demonstration

A dedicated study for on-ground demonstration of formation flying has been conducted by ASTRIUM for ESA, named Formation Flying Ground TestBed FFGTB (ESA contract 19732/06/NL/HB). Therein the whole hierarchy of metrology and control loops up to science mode acquisition is discussed in detail, referring to the reference missions XEUS and DARWIN. Additionally their respective verification approaches have been discussed. With respect to nulling interferometry the recommended approach is partially dependent on the actually selected mission architecture.

Demonstration mission

Whereas FFGTB was focussed on formation flying demonstration on-ground, ESA is now intending to implement the PROBA-3 demonstration mission, demonstrating XEUS formation flying performance requirements. Astrium led the Phase A study for Proba-3 which included analysis of formation flying performance requirements relevant to the L2 environment needed for an exoplanet mission.

Finally ASTRIUM is strongly involved in the CNES/ASI SIMBOL-X formation flying mission, which will enter into a competitive B2/C/D/E phase ITT in fall 2008.

Micropropulsion status

Beyond reaction wheels with their intrinsic variable microvibrations, three classes of micropropulsion thrusters are in different stages of development, all with major ASTRIUM involvement:

- GAIA proportional cold gas micropropulsion, currently in qualification for GAIA, has been analyzed to be suitable for precision-pointing of future single spacecraft missions (possibly EUCLID), with ASTRIUM being GAIA prime.
- FEEPs (field emission electrical propulsion), in qualification for LISA Pathfinder, with ASTRIUM being prime. FEEPs are the baseline propulsion systems for formation flying nulling interferometers, though with about 10x higher thrust as for LISA and LISA Pathfinder.
- Recent µ-RIT developments (Xenon electrical propulsion) by ASTRIUM Space Transportation and University Giessen display promising results and might represent an alternative to FEEPs for nulling interferometers in terms of noise and thrust levels

This list is not complete as there are further subsystems in development, but shall clarify where ASTRIUM can provide synergies for exo-planet missions from experiences in other science mission contexts.

3.3 Nulling interferometry science beam control

Within the FFGTB study, the science beam control for nulling interferometry has been discussed in detail. A step-by-step approach for on-ground demonstration has been proposed, and the final state is depicted below:

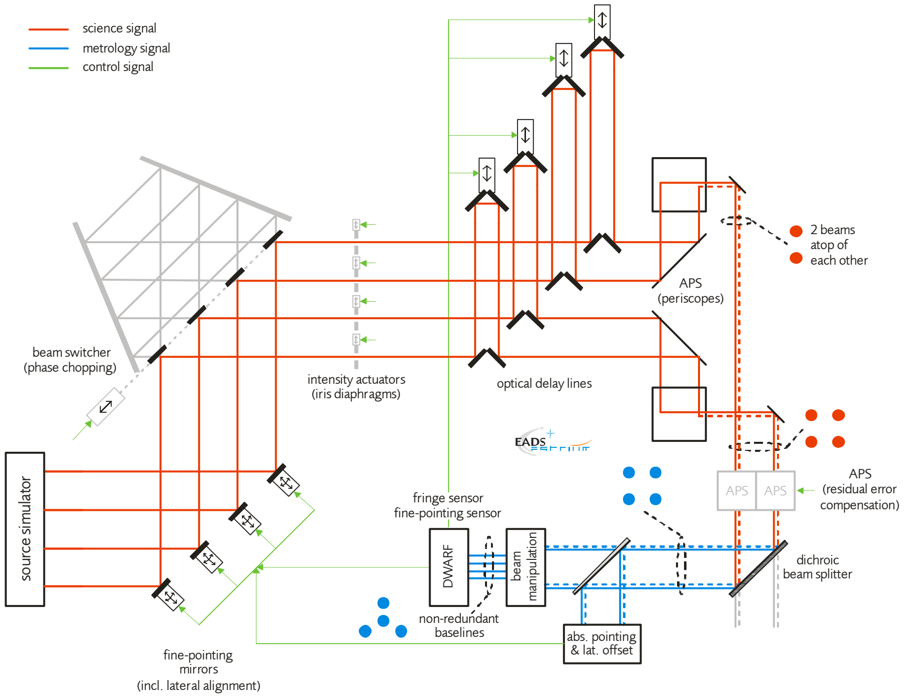

Fig. 3.3-1 Generic setup of the science beam metrology and control functional chain testbed.

Here the performance requirements and implementation details are strongly dependant on the actually selected mission architecture. In a final stage this science beam control testbed can be combined with the Nulling cryogenic testbed, see Fig. 3.1-1.

3.4 Coronagraphy

The most relevant testbeds, specific for coronagraphy, are:

- Star suppression subsystem testbed, requiring breadboarding of several alternative candidate technologies
- Wavefront control subsystem and longterm stability

As mentioned before a European strawman mission design for one selected star suppression subsystem is recommended. Additionally high fidelity optical modelling of diffraction effects within the system is required beyond standard methods (Fresnel instead of Fraunhofer diffraction propagators).

It is recommended also to analyze the combination of a modest coronagraph with an external mid-contrast occulter.

3.5 Mission Analysis

Astrium have been involved in the mission design of several formation flying missions: Numerous in-house tools have been developed to model and design these formations, including optimisation of transfers and assessment of deployment and formation manoeuvring. These tools enable the assessment of the feasibility of mission concepts and generic formation types. They therefore have an integral role in the evolution of current concepts and the generation of new mission concepts. The main new attractive application field would be mission analysis for external occulters.

3.6 System complexity

The mission candidates for exo-planet characterization (nulling interferometry, coronagraphy, or external occultation) all are characterized by an unprecedented technology and mission complexity. On the technical side this calls for the development of a validated end-to-end modelling methodology for the complete system. On the management side this requires well established teams at ESA, the science community, and at industry to handle the full system complexity during the long time of development. ASTRIUM is undertaking internal activities to keep together the know-how built up in previous studies.

4 Conclusion

Missions for indirect exo-planet detection are feasible with the current capabilities concerning technology and system complexity.

The large scale mission candidates for exo-planet characterization (nulling interferometry, coronagraphy, external occultation) still require substantial predevelopment before conclusive industrial trade-offs and decisions can be undertaken.

In particular for nulling interferometry this limited experimental insight resulted in the development of two different mission baselines with substantially different subsystem requirements and complexities. Several subsystem developments have then been undertaken in a competitive and non-public context. A similar criticality is seen for the large variety of different star suppression methods now under discussion for coronagraphy.

Central testbeds in pre-competitive phase

Therefore fundamental central testbeds for various mission options are necessary, with a broad scope and a pre-competitive character. The results and lessons learnt should be available publicly and in a non-competitive way to the interested parties. ASTRIUM offers to support the definition and implementation of such neutral testbeds as possible “steering committee” member, relating testbed definitions and later results to system level aspects in its role as a prime contractor company.

Trading between methods

Whereas in the US design and mission studies for both nulling interferometry and coronagraphy have been undertaken and both concepts have been comparably funded, ESA has focussed on nulling interferometry in recent years. An industrial trade between nullling interferometry, coronagraphy, possibly combined with external occultation, currently cannot be undertaken on technological insights, but has to be systematically prepared by further testbeds, and additionally has to take into account programmatic and scientific arguments.

To conclude, ASTRIUM has been continuously engaged in exo-planet science and technology, and is willing to maintain its engagement in current and preparatory activities of the forthcoming ESA exo-planet roadmap.