An optimized nulling ground based demonstrator for DARWIN: the ALADDIN proposal

Olivier Absil, Laboratoire d'Astrophysique de Grenoble, France
Marc Barillot, Alcatel Alenia Space, Cannes, France
Vincent Coudé du Foresto, LESIA, Observatoire de Paris, France
Denis Defrère, Université de Liège, Belgium
Emmanuel Di Folco, Observatoire de Genève, Switzerland
Carlos Eiroa, Universidad Autonomia de Madrid, Spain
Tom Herbst, Max-Planck-Institut für Astronomie, Germany
Claude Jamar, AMOS, Belgium
Jean Surdej, Université de Liège, Belgium
Farrokh Vakili, Université de Nice Sophia-Antipolis, France

Contact: vincent.foresto@obspm.fr

ABSTRACT

We present here a ground-based mission which is optimized to study the exozodiacal dust around nearby solar-type stars. The objective is the same as the goal that led to the ESA phase A study for the GENIE nulling instrument at the VLTI: pave the way for future space missions dedicated to the spectroscopic IR characterization of exo-Earth atmospheres, by investigating one of the major, and least known, noise sources in the direct detection telluric exoplanets. An antarctic nuller is the optimal ground-based answer for this purpose, providing with relatively modest 1m apertures a capability that outperforms a pair of 8m telescopes on a temperate site.

The ALADDIN concept is an integrated Antarctic-based L-band nulling breadboard with relatively modest collectors (1m) and baseline (<40m). Because of its privileged location, this is sufficient to achieve a sensitivity (in terms of detectable zodi levels) better than GENIE at the VLTI, bringing it to threshold value (~30 zodis) identified to carry out the DARWIN precursor science. These estimations are based on a preliminary design study by Thalès Alenia Space and were obtained using the same simulation software as the one employed for GENIE. The integrated design enables top-level optimization and full access to the light collectors for the duration of the mission, while reducing the complexity of the nulling breadboard.

We propose that ESA includes an Antarctic option when studying potential precursors to a space-based nulling mission.

2. INTRODUCTION - BACKGROUND

A separate white paper by Ollivier et al. stresses the important role played by exozodiacal dust for the feasibility and dimensioning of a mission dedicated to the discovery and IR (7--20µm) characterization of habitable exoplanets. Indeed, if one takes the solar system as an example, the intensity of the IR flux emitted by zodiacal dust (1 zodi by definition) is 300 times brighter than the Earth. Fluctuations of this radiation can be a significant noise source for the survey of exoearths, and may even jeopardize detection for dust clouds brighter than ~30 zodi for nearby targets (see Figure 1). This calls for a survey of exozodiacal dust clouds down to that sensitivity level, around potential targets, in order to retire risk on the space mission and not waste time on sources where exoearths cannot be detected.

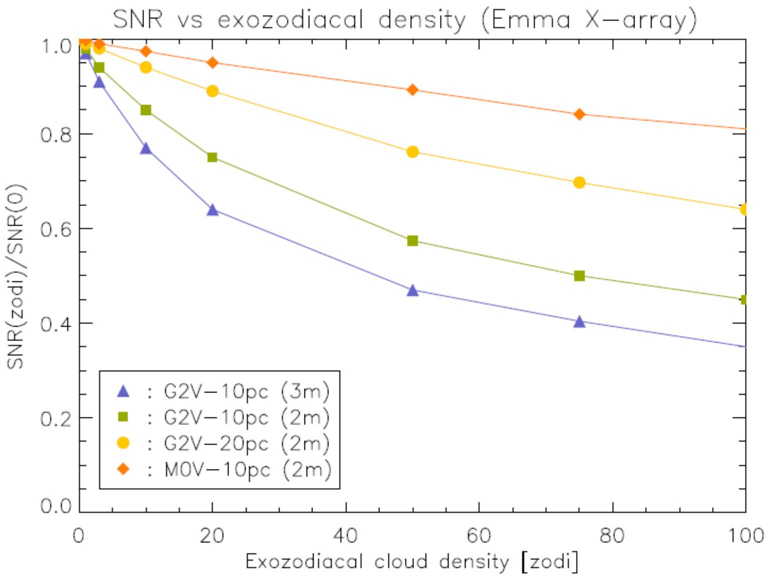


Figure 1 : Effect of the exozodiacal dust cloud density on the sensitivity of DARWIN/TPF. In the case of a bright nearby star (G2V at 10 pc) and with the foreseen 2-m size telescopes, the SNR is reduced by a factor 0.7 (i.e., the integration time multiplied by 2) for an exozodiacal disk density of 30 zodi. The tolerated amount of exozodiacal dust is relaxed for fainter targets (with an upper limit of ~100 zodi due to possible blobs/clumps in the exozodiacal brightness distribution).

It appears that four factors are keys to the success of a ground-based precursor of space nulling demonstrator:

- The breadboard should be designed in such a way that its *concept focuses on issues relevant to the space mission* (nulling, phase stabilization, data analysis), avoiding as much as possible design and engineering challenges which are circumstantial to the demonstration experiment (such as interfaces to an outside system, control loops not needed in space etc.);
- Because of the complex nature of an interferometer and the many real time interactions between its separate elements, the ultimate performance can only be achieved if the *design is optimized at the system level*;
- The *quality of the site is critical* and drives the final performance of the system. Therefore the experiment has to be located on the best accessible ground-based site. As for any interferometer subject to atmospheric turbulence, the largest possible seeing cell size is required to maximize the number of coherent photons. But most importantly, turbulence needs to be slow as it relaxes the requirements on the control loops and enables lower residuals. Finally, for efficient nulling in the infrared a low and stable background is required;
- The nulling demonstrator is a pathfinder mission and should be conceived as such, integrating development, deployment and operations (for a well defined time frame) into the concept.

The ALADDIN (Antarctic L-band Astrophysics Discovery Demonstrator for Interferometric Nulling) proposal results from these considerations.

3. SITE SELECTION

Dome C, on the high Antarctic plateau (elevation 3250m and -75 degrees latitude), is the site of the French-Italian Concordia station and a very unique environment whose main characteristics have been studied over the last few years. It is now identified as the best accessible ground based location for infrared interferometry. This is mostly due to the fact that most of the turbulence is concentrated near the ground. Above that layer (> 30m), only the free air seeing remains. First winter data were obtained with an automated MASS scintillometer (Lawrence et al. 2004) and show that in 2004 over a 3-month period, the median free air seeing was 0.27" (compared to 0.80" at Paranal), while 0.15" was achieved more than 25% of the time. Winter statistics for the height of the ground layer have been monitored by Fossat et al. (2008). While the mean height is around 30m, being only 15m above the ground would guarantee for an instrument to be in the free atmosphere for a significant fraction of the time. Also, in the summer the free atmosphere extends to the ground level for a few tens of minutes each day (as the temperature gradient gets nulled). Note that the height of most observatories is above 15m from the ground.

Still more important than the seeing angle, turbulence at Dome C is slow, which would result in a considerably improved performance (lower residuals) for the phase control loops of an interferometer. The normalized coherence time τ_0, as measured with the MASS scintillometer, has a median value of 7.9ms (vs. 2.6ms at Paranal), while direct DIMM measurements show a correlation of the image motions beyond 250ms. Combining the gains in coherence time and seeing cell size r_0 means that, under median conditions, the coherence volume (proportional to c. $\tau_0 . r_0^2$) in which coherent photons can be used for interferometric operation is increased by a factor 26 with respect to Paranal.

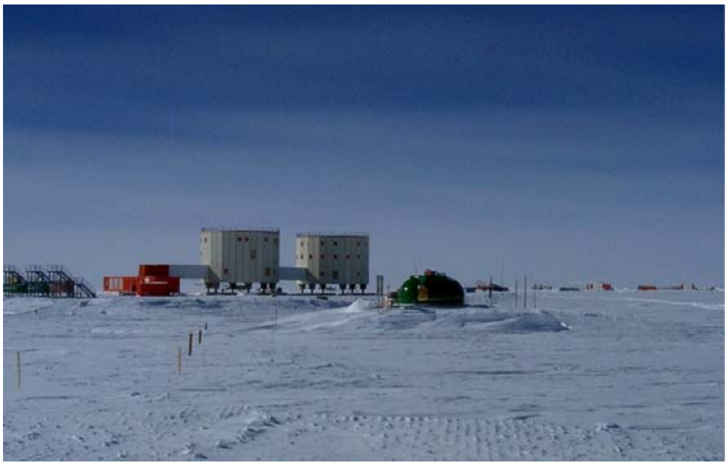


Figure 2 : The Concordia station at Dome C.

Additional features of Dome C are unique to a ground-based site and particularly attractive for nulling interferometry in the infrared:

- Low ambient temperatures (ranging from 195K in the winter to 240K in the summer) result in reduced, stable thermal emission;
- An extremely dry air (250µm PWV typical) results in enlarged and improved IR transmission windows, and reduced fluctuations of the chromatic dispersion. Altogether, the combination of coldness and dryness for the atmosphere results in IR photometric gains that peak at about x25 in the K and L bands (with respect to a temperate site);
- Very low surface winds (the median wind speed is 2.7m/s; less than 5m/s more than 90% of the time) result in lower structural vibrations.

The Dome C site is accessible with logistics developed by the French (IPEV) and Italian (PNRA) polar institutes. The capacity of the station is about 40 people in the summer and 16 people during the winter-over. People reach the site by plane with a total travel time of about 48h from Europe, while the heavy equipment is shipped in standard containers by boat to the coast and then by "traverses" (pack trains of Caterpillar trucks) onto the glacier slopes up to Concordia. Dome C thus provides a near space quality environment for infrared interferometry at a small fraction of the access cost. Finally the nature of the site, halfway between ground and space, makes it a privileged area for collaboration between ESO and ESA if so desired.

4. INSTRUMENT OVERVIEW

A preliminary design for an Antarctic based integrated nulling experiment was studied by Thalès Alenia Space (Barillot et al. 2006) and is briefly outlined below. It will be used as a basis for performance simulations in the next section. Its main features are:

- Two collectors (1 meter beam diameter in the nominal version) are located on a 40m rotating linear truss so that the source can always be maintained at the meridian of the baseline, thus avoiding the need for a long movable delay line;
- Collectors are off-axis siderostats, and telescopes provide beam compression down to 18mm. The collectors can slide along the truss (but remain fixed during observations) to *optimize the baseline (and stellar leaks) for a given source*. The baseline length can take any value from 4.3m to 30m;
- The compressed beams are derotated to enter the nulling beam combiner bench which can remain fixed to the ground (no microvibrations perturbations at this level);
- The nulling bench (2.4x0.9m) is located in a cryostat for lower thermal emission and better stability. It is similar to the single-bracewell version of GENIE, but simplified as the *dispersion compensation and intensity control loops turn out to be no longer necessary* with this configuration. Thanks to the better transparency of the atmosphere towards the lower end of the L' band, the *wavelength coverage of the science channel is extended* to 3.1-4.1µm, whereas the K band throughput is sufficient for fringe tracking.

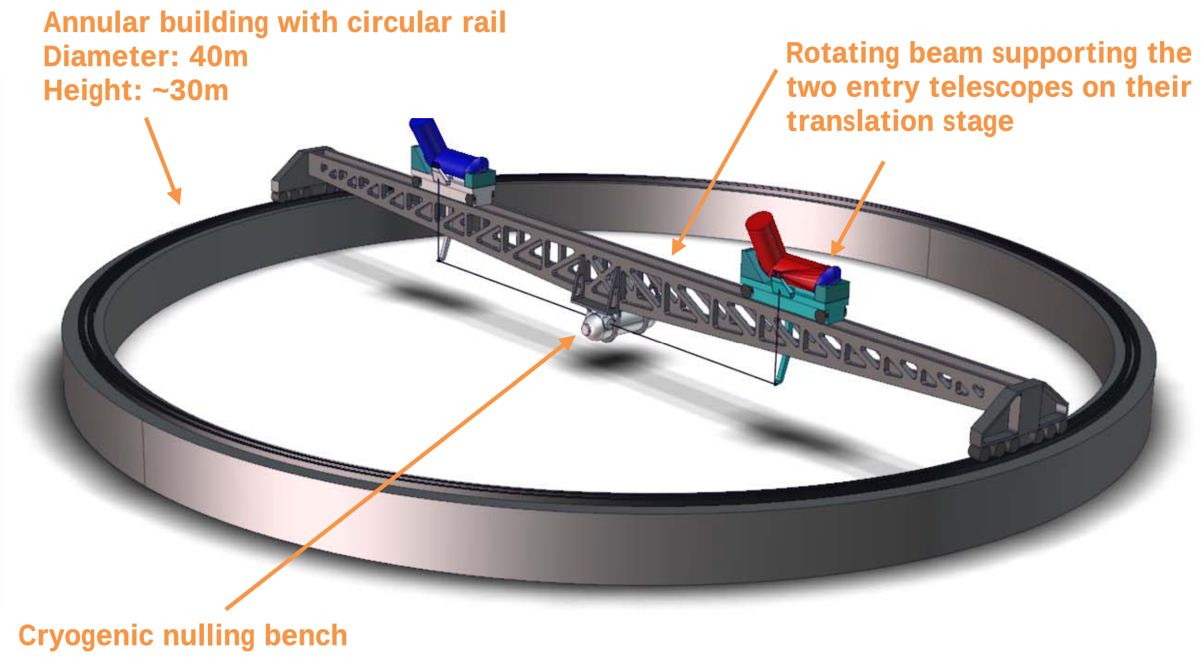


Figure 3 : Initial ALADDIN design.

Compared to GENIE at the VLTI, the ALADDIN concept requires the construction of dedicated collectors. They have a moderate size, but must be installed relatively high above the ground to avoid the ground layer. This additional effort, however, is balanced by the many simplifications and optimizations (some on critical GENIE issues) brought by the integrated design and the Antarctic location. For example:

- In addition to the gains brought by the site, the optical throughput and overall emissivity is enhanced by the integrated design: there are only 5 warm optical surfaces (vs. 21 for the VLTI) from the sky to the entrance of the cold optical bench. The off-axis design suppresses the thermal emission from the secondary support structure and improves fiber coupling;

- The required polarization stability at beam collection is intrinsically easier to achieve as the incidence angle on the siderostats does not change, to a first order, during the observation: since the source is maintained at the meridian of the baseline, it depends only on its elevation, which varies little with hour angle (around maximal elevation) due to the near-polar location of the site;
- Real-time control loops are limited to tip-tilt control and phase stabilization; due to longer coherence time they can run at lower (non critical) closed loop frequencies. For example, on a G0V star at 10pc GENIEsim calculations show that a reasonable 3kHz loop rate (using photons from the K band only) is sufficient to maintain the piston residuals below 14nm rms. Tip-tilt compensation can be run at a relatively easy 1kHz with 9mas residuals. Besides, *a difficult control loop (dispersion compensation), not relevant for a DARWIN demonstration, is no longer needed with ALADDIN*.
- There are no interfaces to an existing, external system: this results in both a design simplification and a minimization of risk during development and integration;
- Likewise the performance of ALADDIN can be modelled with greater confidence as it does not rely on the nominal performance of an external system;
- Calibration capabilities are improved by:
    - The possibility, for a given source, to monitor the stellar leaks at an arbitrary baseline;
    - The possibility to invert the collectors for a given baseline length (rotating the truss by 180°);
- Finally, access of the breadboard to the sky is available during the full duration of the experiment, and not limited by telescope time allocation.

5. EXPECTED PERFORMANCE

A performance evaluation of ALADDIN was achieved using the same GENIEsim software that was developed by Absil et al. (2006) to assess the performance of GENIE at the VLTI (see SAT report), using as an input the specifications of ALADDIN as derived from the Thalès Alenia Space study, and the median atmospheric properties of Dome C above the ground layer as published by Lawrence et al. (2004). The results for this nominal configuration have been developed and compared with performance of other ground-based and space-based nulling interferometers in two separate papers (Absil et al. 2007 and Defrère et al. 2008), which are summarized in Figure 4 for the case of the four fiducial stars used to evaluate the performance of GENIE.

Everything else being equal, *the sensitivity of ALADDIN (in terms of level of exozodis) is always better than the sensitivity of GENIE at the VLTI, or any other ground based interferometer*. As can be expected, the gain is largest for bright nearby stars which benefit most from the adjustable baseline. It is lowest for faint stars, such as G-type stars at 20-30pc. The sensitivity of ALADDIN, which ranges between 30 and 60 zodi, can be improved on faint targets by increasing the integration time, leading to sensitivities in the 20-30 zodi range for G-type stars between 10 and 30pc. It can also be improved on bright targets by simultaneously fitting the stellar diameter and the exozodiacal disk brightness to the measured nulling ratios at various baselines, reaching a 5σ detection level of about 35 zodi for a K0V at 5pc using ten 30-min observations (see Absil et al. 2007). ALADDIN can therefore fulfil the 30-zodi performance requirement on most DARWIN/TPF target stars.

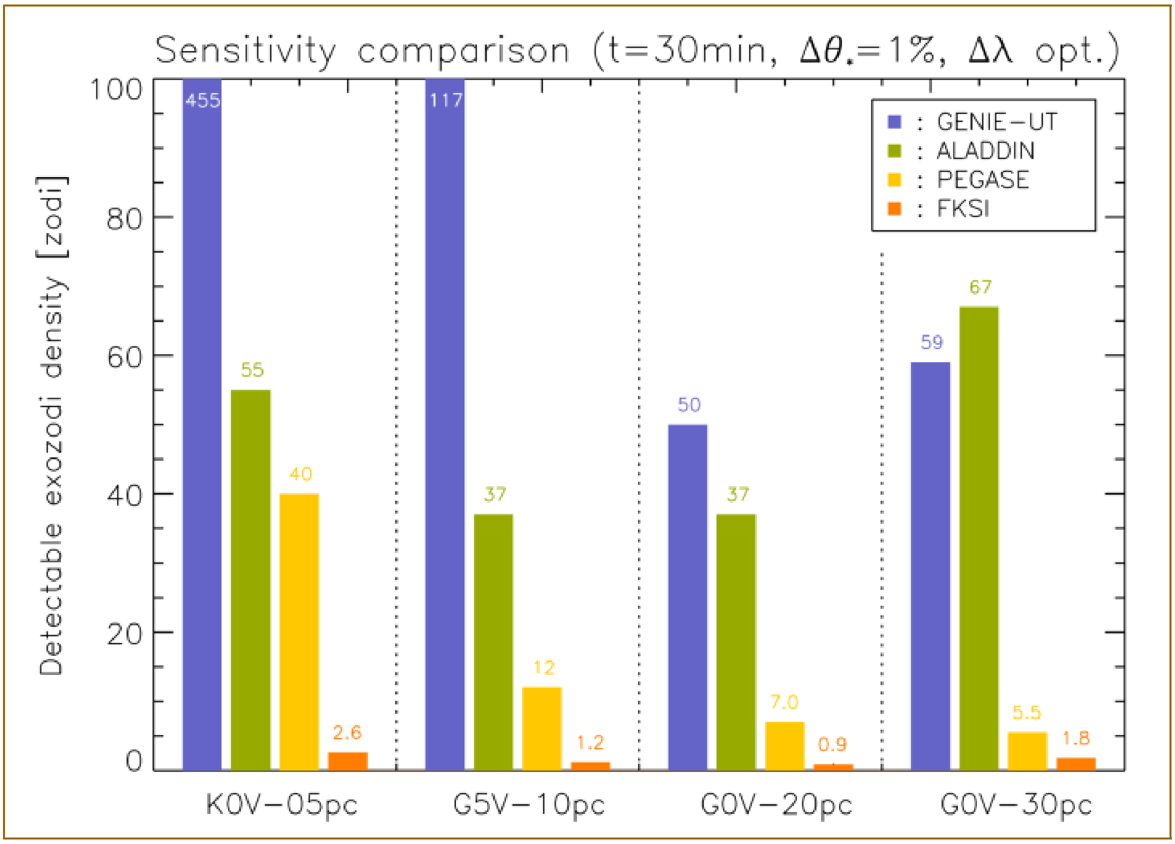
A consequence of the better sensitivity of ALADDIN is that, while the number of *observable targets* is smaller due to the more southern location of the experiment, *the number of targets for which the precursor science can be done is actually increased* with respect to other ground-based nulling interferometers located in temperate sites such as VLTI/GENIE or the Keck Interferometer Nuller (which has a typical sensitivity of 100 zodi and is restricted to the observation of very bright stars). It must be noted that the Large Binocular Telescope Interferometer (LBTI), which is foreseen to come online in 2010, will operate in nulling mode on two co-mounted 8-m apertures in the mid-infrared and is expected to reach a 5-sigma sensitivity in the 10-20 zodi range in 1h for bright targets (e.g., G-type dwarfs within 10 pc) thanks to an optimised design (Hinz et al. 2008). The complementary sky coverage offered by the LBTI (Northern hemisphere) and ALADDIN would be an asset in the preparation of future all-sky space-based missions.

II.1 GENIE (Ground-based European Nulling Interferometry Experiment)

- Nulling interferometer for VLTI (Paranal, Chile) [1]
- Simulation on 8-m Unit Telescopes
- Baseline range: 46 – 130 m
- Wavelength range: 3.5 – 4.1 µm
- Control loops: wave front, piston, dispersion, intensity
- r_0 = 13 cm
- τ_0 = 3 msec
- Sky temperature = 285 K
- RMS precipitable WV = 27 µm

II.2 ALADDIN (Antarctic L-band Astrophysics Discovery Demo for Interfero Nulling)

- Nulling interferometer for Dome C [4]
- Assumes 1-m siderostats
- Baseline range: 4 – 30 m
- Wavelength range: 3.1 – 4.1 µm
- Control loops: tip-tilt, piston
- r_0 = 38 cm
- τ_0 = 8 msec
- Sky temperature = 230 K
- RMS precipitable WV = 1 µm

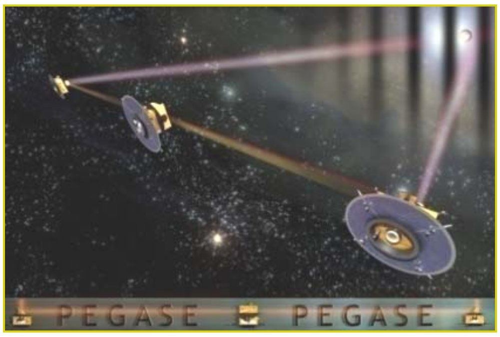


II.3 PEGASE

- Free-flying nulling interferometer [5]
- 2 collectors (40 cm) + 1 combining spacecraft
- Lagrange L2 point
- Control loops: tip-tilt, piston
- Baseline range: 40 – 500 m
- Wavelength range: 1.5 – 6.0 µm
- Optics temperature: 90 K
- Detector temperature: 55 K

II.4 FKSI (Fourier-Kelvin Stellar Interferometer)

- Structurally connected nulling interferometer [5,6]
- 50 cm telescopes
- Lagrange L2 point
- Control loops: tip-tilt, piston
- Baseline: 12.5 m
- Wavelength range: 3 – 8 µm
- Optics temperature: 65 K
- Detector temperature: 35 K



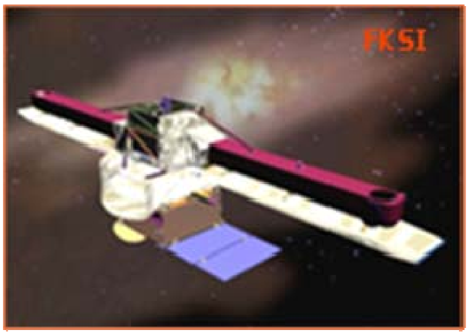


Figure 4 : Performance comparison for ground-based and space-borne nulling interferometers, in terms of detectable exozodiacal disk density level (integration time: 30 min). Additional details can be found in Defrère et al. (2008).

6. TENTATIVE DEVELOPMENT PLAN

Surprisingly enough, ALADDIN's development plan can be considered less risky and potentially better consolidated than that of GENIE, for the following top-level reasons:

- The overall and instrumental optical architecture is much simpler;
- The control loops are less numerous, much simpler and slower, overlap less and as results, are less a concern;
- Instrument/architecture interfaces are simpler and can be end-to-end validated before transfer to Dome C;
- ALADDIN is dedicated to a "one shot" two year mission.

As results, the ALADDIN schedule is expected to be compatible with the preparation of a nulling space interferometer.

6.1 INDUSTRIAL BREAKDOWN

The present development approach is based on the industrial breakdown of the ALADDIN System depicted below. *It allows the development to be fully parallelised, which provides schedule optimisation*:

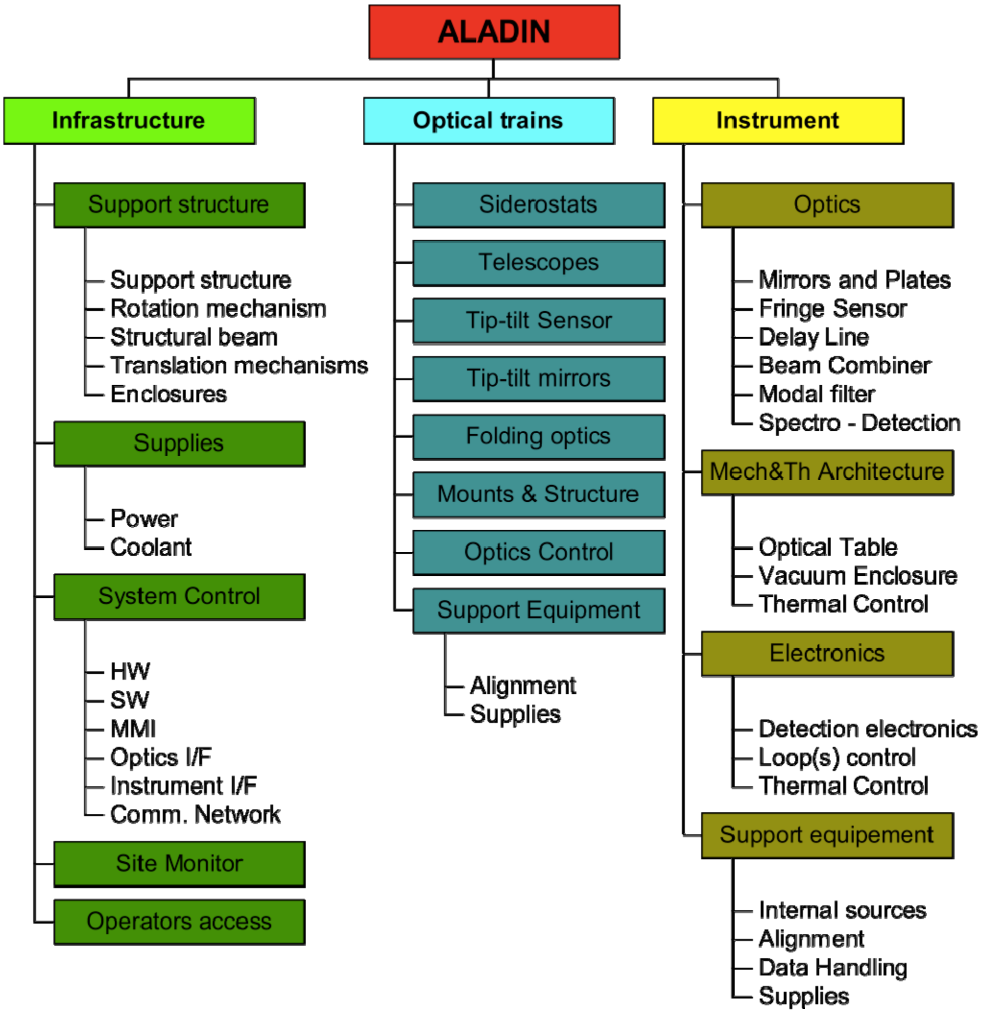


Figure 5 : ALADDIN is split into three well-separated subsystems allowing a parallel development approach.

6.2 CRITICAL ISSUES AND MITIGATION PLAN

6.2.1 Infrastructure critical issues

In a preliminary approach, we have listed the following critical points:

- A support structure must be built in order to protect Aladdin from the perturbed air flow of the lower atmospheric layers. This structure must allow the air above the ALADDIN apertures to continue flowing smoothly as before.
- A rotating 40m-long structural beam must be developed. The criticality essentially results from the Antarctic environment and the sensitivity of nulling interferometry.
- Implementing and running the infrastructure must be compatible with the Antarctic environment and weather, as well as the limitations of the Dome C site, in terms of power, coolant, supply, thermal control and human access and operations.
- The infrastructure must be compliant with the stringent alignment and stability requirements of nulling interferometry.

Mitigation of these issues will be achieved by involving partners with relevant experience in the Team, and starting the studies as soon as from the beginning of an ALADDIN-dedicated study. Moreover, implementation difficulties specific to the Antarctic environment can be mitigated by making sure that the whole experiment works properly before transfer to Dome C is decided. Indeed, ALADDIN includes all necessary infrastructure and support functions and can be considered autonomous, thus enabling an end-to-end functional tests and partial performance validation to be achieved from a European site with easy access.

6.2.2 Optical train critical issues

The optical trains are expected to be protected from the Antarctic environment by the infrastructure. They benefit from reasonable aperture, little complexity of the optical arrangement when compared to other, already existing, interferometric trains and short mission duration.

However, the sensitivity of nulling interferometry is likely to provide stringent requirements at the stability level. Damping of the vibrations generated by the various mechanisms (beam rotation, siderostats motion, tip-tilt actuation are to be taken into account). Mitigation of these issues will be achieved by starting opto-mechanical design, vibration modelling and analysis as soon as from the beginning of an ALADDIN-dedicated study.

6.2.3 Instrument critical issues

The instrument critical issues can be considered to be qualitatively the same as GENIE's. Fortunately, on the quantitative point of view, the dramatic simplification of the ALADDIN instrument with respect to GENIE provides a significant relaxation of the effort and risks associated to the development. Namely:

- The need to demonstrate stable deep nulling at the 3.8µm wavelength remains a critical issue, though it should be made easier thanks to the simplification of the optical arrangement.
- The need to adjust high performance control loops remains a critical issue, though the dispersion control and intensity matching loops have disappeared, and the loop frequencies are expected to be strongly reduced.
- Background calibration accuracy remains a critical issue, though the strongly reduced number of components, the reduced temperatures and the better stability of the sky are likely to greatly relax the criticality.
- Stellar diameter calibration accuracy issues are still to be mentioned as critical issues, though the capability to continuously adjust the baselines provides additional information and degree of freedom to the process.

6.3 DEVELOPMENT LOGIC – REVIEWS – PRELIMINARY SCHEDULE

The preliminary development logic is in line with those usually put in place by organisations such as ESA or ESO. The basic idea is to solve technological issues as early as possible, at component or equipment levels wherever possible.

Reviews summarise the clearing of the critical issues at each step and give the go-ahead for the next step. The major steps and the expected timeline are the following:

- Consolidation of the ALADDIN file to the PDR level can be achieved within 1 year (and possibly less thanks to the strong commonality with the GENIE Definition Phase study).
- Instrumental development is supposed to be as long as that of GENIE, a conservative statement given the simplification of ALADDIN wrt. GENIE.
- A 3-year period is allocated to the design and technological validation of the infrastructure and optical trains in Europe.
- A complete "System Integration and functional tests Europe" is planned in a temperate environment, including functional tests on the sky, in order to clear up all possible interface issues and perform an end-to-end rehearsal of the integration activities at Dome C. Such a consolidation of the Development Plan is made possible by the end-to-end nature of ALADDIN: the experiment includes all necessary infrastructure and support functions and can be considered autonomous.
- Implementation at Dome C is assumed to take 6 months (summer period) followed by the functional tests and commissioning on the sky (winter period).
- Scientific results can be expected in 5 years after the formal start of the project, early enough for being fed-back into studies for a space mission.

7. CURRENT ACTIVITY

A working group was created within the ARENA network for the development of Antarctic astronomy. Its goal is to refine the definition and to realize a pre-feasibility study of an Antarctic interferometer dedicated to the characterization of exozodiacal disks with the sensitivity required (5σ detection of 30-zodi disks) to discriminate sources suitable for future exo-Earth detection. The engineering study is carried out at AMOS, based on a concept by Thalès Alenia Space. Particular emphasis is being put on the compatibility with Concordia logistic and operational constraints, for which input is provided by the French polar institute IPEV. The group will submit a first report by the end of 2008 (http://arena.unice.fr/article.php3?id_article=129), and a final report for the ARENA III conference (http://arena.unice.fr/article.php3?id_article=142). If the results are positive, a work plan will be outlined for a design study that could be submitted to FP7 and/or to ESA.

ARENA interferometry working group membership:

Coordinators:

V. Coudé du Foresto (LESIA, Obs. Paris)
J. Surdej (U. Liège)

Industry & agency partners:

C. Jamar (AMOS, Liège)
M. Barillot (Thalès Alenia Space, Cannes)
Y. Frenot (IPEV, Brest)

Science support team

O. Absil (LAOG, Grenoble): modelization
E. Di Folco (Geneva Obs.): observing strategies
C. Eiroa (UAM Madrid): input catalog
T. Herbst (MPIA Heidelberg): comparison with LBT
F. Vakili (Fizeau, Nice): instrumental concepts

8. CONCLUSION

It appears that Dome C is the most effective location from which one could build a relatively modest (~20M€) nulling interferometer that would carry out the preparatory science required for future space missions dedicated to the spectroscopic characterization of exo-Earths. This is a formidable opportunity for the space program since risk can be retired on a major mission for a small fraction of its cost, and we believe that this path is worthwhile pursuing.

9. REFERENCES

Absil O., Coudé du Foresto V., Barillot M., Swain M. R., 2007, *A&A* **475**, 1185

Agabi A., et al., 2006, *PASP* **118**, 344

Barillot M., et al., 2006, *SPIE* **6268**

Defrère D., et al., 2008, *A&A* (in press)

Fossat E., et al., 2008, *A&A* (in press)

Gondoin P. A., et al., 2004, *SPIE* **5491**, 775

Hinz P. M., et al., 2008, *SPIE* **7013** (in press)

Lawrence J., et al., 2004, *Nature* **431**, 278