

**THALES**



**DIEHL**  
BGT Defence

# **ATLAS**

## **Executive Summary**

Short Public Version

---

### **ADVANCED TECHNIQUES FOR LASER BEAM STEERING (ATLAS)**

---

**EUROPA MOU - RTP 108.085**

## Identification of the document

<b>Title</b>	Executive summary – Short Public Version
<b>Version</b>	creation
<b>Deliverable id.</b>	D23 public version
<b>Document id.</b>	ES/4/TO/03
<b>Date</b>	19/12/08
<b>Originating partners</b>	TOSA, TRT, DBD, GA
<b>Responsible partner</b>	TOSA
<b>Relevant Work Package</b>	WP 0
<b>Relevant Task</b>	-
<b>Release Status</b>	issued
<b>Classification</b>	none
<b>File reference</b>	D23_ATLAS_shortpublicversion.doc
<b>Distribution list :</b>	DGA/SPART, ONERA, EDA, DGAT-IT, WTD81, FGAN-FOM  Thales Research and Technology  Galileo Avionica  Diehl BGT Defence  Thales Optronique, Thales DLJ

# CONTENT

<b>1</b>	<b>INTRODUCTION .....</b>	<b>4</b>
<b>2</b>	<b>TECHNICAL SUMMARY .....</b>	<b>4</b>
2.1	DEVELOPMENT OF FINE BEAM STEERING COMPONENTS AND DEVICES .....	4
2.2	DEVELOPMENT OF COARSE BEAM STEERING DEVICE .....	6
2.3	DEMONSTRATION OF COMBINED COARSE/FINE BEAM STEERING DEVICE .....	7
2.4	DEMONSTRATION OF LASER ARCHITECTURE WITH BEAM STEERING .....	7
2.5	ENGINEERING STUDIES .....	8
<b>3</b>	<b>READINESS LEVELS AND APPLICABILITY OF TECHNOLOGIES.....</b>	<b>10</b>
<b>4</b>	<b>CONCLUSIONS - RECOMMENDATIONS .....</b>	<b>10</b>

# 1 INTRODUCTION

This report presents an Executive Summary of the work performed and results obtained in the frame of the ATLAS project (Advanced Techniques for LA beam Steering) from December 2005 to June 2008. The main contractor and SLIE has been Thales Optronique SA (TOSA, France), with Thales Research & Technology (TRT, France), Diehl BGT Defence (DBD, Germany) and Galileo Avionica (GA, Italy, now Selex Galileo) as subcontractors.

The objective of the project was to investigate innovative concepts for non-mechanical beam steering and beam shaping of laser based systems, as a follow-on of the THALES JP 8.11 on Laser Beam Steering. The project has aimed at developing technological bricks and demonstrating related new concepts at laboratory level, for mid term application (operational systems around 2015).

The main military functions and applications identified are related to infra-red counter-measures, long range recognition/identification, designation, ranging and tracking of military targets, with multi-target capability. These applications require a precision laser beam pointing system suitable for fitting to a fast jet and capable of precisely pointing a mid IR laser beam at an airborne or ground target, for self protection through missile jamming or long range identification and tracking through high resolution active imaging.

The investigations, covering the 1.5  $\mu\text{m}$  range and also the 3-5  $\mu\text{m}$  range, have been performed on following techniques/technologies by TRT and DBD :

- for fine beam steering : electro-optic ceramics and liquid crystal based light modulators;
- for coarse beam steering : micro-lens arrays;
- for laser architecture with beam steering : intracavity beam steering, Fourier Transform OPO for wavelength conversion.

The objectives of performances for ATLAS components have been derived from the analysis of the operational needs and requirements, considering the operational functions envisaged (acquisition, tracking and neutralization of attacking missiles by laser, active imaging, range finding and targeting, LIDAR) and related technical functions (successive pointing with wide angular deviation or continuous and fast scanning of a zone). Corresponding major technical characteristics have been evaluated for each component within a dedicated Common Evaluation Plan. In addition, laser induced damage tests, as well as environmental tests, have been performed by GA on most of the components.

The work on technologies has been completed by the demonstration of concepts at lab level, engineering studies and revision of components capabilities and systems applicability.

## 2 TECHNICAL SUMMARY

### 2.1 DEVELOPMENT OF FINE BEAM STEERING COMPONENTS AND DEVICES

Fine steering devices (FSD) are components that operate a high resolution (or continuous) scanning of the laser beam. The FSD devices developed in ATLAS by TRT were of two kinds : electro-optic (EO) prisms and phased arrays. For both architectures, the beam steering is achieved by imprinting an electro-optically induced phase tilt to the incoming laser beam, thus deflecting it. The fundamental difference between the two architectures is that for the prism, the phase tilt is continuous, whereas for the phased array, the phase tilt is discrete, sampled along the individual phase modulators that constitute the array. This discrete structure allows the phased array to be combined with a large angle steering device such as the micro lens arrays developed by DBD in ATLAS (see § 2.2). The technology used for the prisms relied on EO ceramics PLZT and PMN-PT, whereas phased arrays were developed based on two different technologies :

- EO ceramics PLZT and PMN-PT, which are known and mature materials, with high EO coefficient, large transparency window (500nm-7 $\mu$ m) and  $\mu$ s-range response time,
- micro/nano Polymer-Dispersed Liquid-Crystal ( $\mu$ /n-PDLC), which have a lower maturity level, and for which additional work was required at material level. In particular, the n-PDLC is a promising solution to further improve the response time of usual liquid crystal, as the droplet size is considerably reduced, but the technology state of the art at the beginning of the ATLAS project did not allow to achieve sufficient phase delay for a beam steering function.

1) **The PLZT and PMN-PT prisms** are bulk transparent isotropic ceramics that were designed and experimentally characterized at 1.5  $\mu$ m. A 5mrad maximum steering angle was demonstrated, with 36 resolved directions. The PMN-PT prism was found to be more efficient than the PLZT one. The prism component was shown very robust to thermal and vibration exposure. Complementary investigations have been performed in the full 0.4 – 6  $\mu$ m range : there is almost no absorption from 1  $\mu$ m to 5  $\mu$ m, and there is no significant change in electro-optic efficiency between 1.5  $\mu$ m and 4  $\mu$ m up to 2V/ $\mu$ m (with higher efficiency of the PMN-PT material), whereas at voltages higher than 2V/ $\mu$ m, the saturation of the EO effect in PMN-PT only leaves PLZT as efficient material with higher index change.

2) **The EO ceramics phased array** consists in an array of equally spaced phase modulators, processed in the EO ceramic. As depicted on Fig. 1, each phase modulator is obtained by etching a pair of trenches in the material, which, after metal deposition, will act as volume, or embedded, electrodes.

Both PMN-PT and PLZT phased arrays were developed, with 64 interdigitated electrodes, but only the PMN-PT device was evaluated for the beam steering function (correct  $2\pi$  phase shift generation at 1.5  $\mu$ m within the available applied voltage range). It demonstrated a 7.5 mrad maximum steering angle and 64 resolved directions, with around 10% beam steering efficiency and 1  $\mu$ s response time.

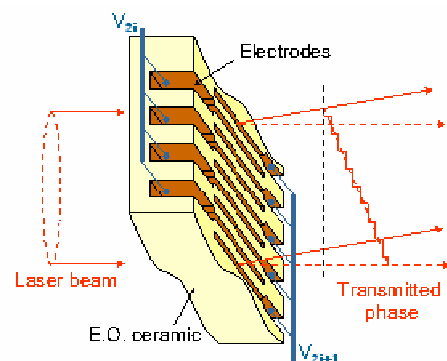


Fig. 1 : Electro-optic ceramic phased array

For 3-5  $\mu$ m operating, design guidelines have been derived from the measured optical and electro-optical properties of both materials, taking into account the technological limit of electrode aspect ratio.

3) **The PDLC phased array**, as shown on Fig 2, consists in a set of individual EO phase elements, based on PDLC material filled in the gap of cells. These active cells are defined between two IR optimized substrates separated by interdigitated metallic electrodes, grown onto one of the substrates.

The work first performed at material level has shown that :

- classical  $\mu$ PDLC (1  $\mu$ m droplets) is well suited for beam steering in the 4-5  $\mu$ m range, offering a well mastered high concentration of liquid crystal (80% of weight), leading to a high refractive index change; a low driving voltage ; a large thickness achievable (500  $\mu$ m), leading to a large dephasing. In addition, this material is robust to important temperature changes as demonstrated by thermal exposure test.

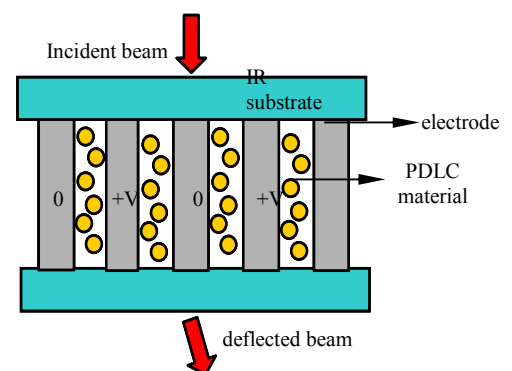


Fig. 2 : PDLC phased array principle

- nPDLC (200 nm droplets) is better suited for beam steering at 1.5  $\mu\text{m}$  (less scattering), once the limitation of state-of-the-art low liquid crystal concentration (30% of weight) and small achievable thickness (30  $\mu\text{m}$ ) has been overcome : a specific process using UV laser polymerisation has been developed to increase these key parameters and achieve the required  $2\pi$  phase-shift at 1.5  $\mu\text{m}$  per single element. This original ATLAS process has allowed to achieve a 130  $\mu\text{m}$  thickness with a well mastered nano-droplet regime. On the other hand, this material cannot stand high temperature change, as the isolated droplets burst and make then the laser beam too much disrupted.

As a result of these investigations and developments, a nPDLC phased array has been designed and tested at 1.5  $\mu\text{m}$ . A dedicated optically addressed electronic driving board has been designed to allow individual commutation of high voltage (1-2kV) on each array element for  $2\pi$  phase delay at 1.5  $\mu\text{m}$ . With a 100V bias voltage to prevent residual scattering of the EO material, the device has demonstrated the capability of nPDLC material for beam steering at 1.5  $\mu\text{m}$ , with advantages in terms of transmission, efficiency and power consumption. The beam steering efficiency was found to be around 35%, with 15 resolved directions and around 200  $\mu\text{s}$  response time in the on-state.

## 2.2 DEVELOPMENT OF COARSE BEAM STEERING DEVICE

The coarse beam steering device (CSD) in ATLAS is based on the micro-lens array technology. Microlens arrays (MLAs) are an arrangement of miniaturized lenses. The diameters of the single lenses forming the arrays are typically in a range from 10  $\mu\text{m}$  to 1 mm. Cascading two MLAs enables blazed grating beam steering. Then the device forms an array of (afocal) micro-telescopes. By laterally displacing one array wrt the other, the wave front behind each micro-telescope gets tilted and an incident laser beam is deflected in the direction perpendicular to the tilted wave front. When illuminated with coherent light (laser), diffraction orders are generated due to the pixelated structure of the device. The beam can be steered only from one diffraction order to the next. The MLAs provide a large steering angle and the number of resolved steering directions coincide with the diffraction orders inside the maximum steering angle.

The micro lenses in ATLAS were designed by DBD to work at 1.5  $\mu\text{m}$ , because the MLA device was intended to be combined with one of the FSDs developed at 1.5  $\mu\text{m}$ . Indeed there is no technological gap between the 1.5 $\mu\text{m}$  and the 3-5  $\mu\text{m}$  ranges for micro-lenses : the substrate of the arrays is silicon, which works in both spectral ranges. The optical system of the micro lenses forming the arrays was designed as a Keplerian telescope setup with field lens.

The MLAs have been realized by the Fraunhofer Institute for Applied Optics and Precision Engineering, with new manufacturing features such as aspheric and double-sided arrays. The MLAs were manufactured on specially selected silicon wafers, using laser writing and reactive ion etching technology. The MLAs quality was verified by the measurement of the fill-factor, the radii deviation of the micro lenses and the maximum optical axis displacement of the double-sided arrays. The achieved performance is today's feasibility limit.

The performed measurements of the experimental setup have proven the high quality of the MLAs and the improved design. In most cases the actual results matched the simulations. It can be concluded that the micro lens design with a Keplerian telescope and field lenses combined with the high quality MLAs improves the beam steering performance significantly. The large useful steering angle (+/- 20°) with  $\pm 23$  resolved directions, and the reduced diffraction effects (1<sup>st</sup> side lobe suppression ratio : - 8 dB) validate the improved performance compared to the former Galilean setups (with estimated response time of 0.7 ms).

## 2.3 DEMONSTRATION OF COMBINED COARSE/FINE BEAM STEERING DEVICE

The combined C/F-BSD consists of the fine steering device, which can be either the PDLC or the EO Ceramics based phased array, and the coarse steering device (micro lens arrays).

As seen in the MLA principle description, with the CSD the beam can be steered only from one diffraction order to the next. By adjusting a phase piston for each MLA micro telescope, steering the beam into directions lying between the diffraction orders of the MLA device becomes possible. This is done by the FSD, which provides a variable phase ramp for each micro telescope. The phase piston for all sub elements is forming a phase ramp which is applied to the micro lens arrays.

The major aim of the lab tests was the demonstration of quasi non-mechanical continuous beam steering with the combined fine steering and coarse steering devices.

For the lab setup the ATLAS one-dimensional PMN-PT based phased array was used as FSD. A straightforward approach was chosen to test and confirm the principle of operation of the combined C/F-BSD in a laboratory environment : the two devices were optically connected with a 0.5 magnification imaging lens, as the FSD pitch was twice the pitch of the micro lenses. The wave front of the fine steering device was transferred to the micro lens arrays via an additional imaging optic. The polarization state of the input beam was parallel to the applied electric field of the polarization sensitive FSD. Then a last lens was used in an f-f arrangement to project the far field image of the MLA output onto a CCD sensor .

The continuous steering function could be proved successfully. All measured parameters were very close to the predicted theoretical values. The large steering angle of the MLA and the high resolution of the FSD led to a large maximum steering angle of +/- 12° with a total number of resolved directions of 1800 (+/-900). Regarding the lower efficiency, the three causes of energy loss in the combined device are Fresnel losses, fill-factor losses, and pixelization losses, i.e. the energy lost in the other diffraction orders. Ways to greatly improve efficiency have been identified and proposed for further development.

The measurements confirmed the successful operation of the combined C/F BSD.

## 2.4 DEMONSTRATION OF LASER ARCHITECTURE WITH BEAM STEERING

Previous components described above all aimed at steering the laser beam directly at the final operating wavelength, 1.5 µm or in the 3-5 µm range. Specific laser architectures have also been studied and demonstrated by TRT within the ATLAS project, featuring laser beam steering at 1 µm followed by wavelength conversion. These kinds of architectures can be interesting in case of poor efficiency of the Beam Steering Device (BSD) at longer wavelength, and in order to have it operated at moderate optical power, the laser beam being amplified after deflection.

For deflection, beside a classical extra-cavity approach based on the maturity and efficiency of COTS steering devices at 1 µm, an original intra-cavity approach has been developed.

Wavelength conversion has been demonstrated with a specially designed FourierTransform OPO (FT-OPO).

- 1) **The intra-cavity beam steering** approach allows to control the deflection angle by an amplitude modulator instead of a phase modulator : by changing the position of a programmable aperture inside a confocal cavity, the beam is deflected. Within ATLAS, a non pixelated optically addressed spatial light modulator (OA-SLM), based on the µPDLC technology, was realized and used as programmable aperture, offering a short response time (40 ms), polarization insensitivity, and reduced voltage driving .

The cavity length, and choice of gain medium geometry and lenses were established from the theoretical study of energetic performances and achievable number of resolved points. The experimental setup used a 4f-folding resonator and a compact large-field of view longitudinally pumped Nd:YAG crystal as gain medium. The OA-SLM inside the cavity was optically addressed by a video projector placed outside the cavity.

The intrinsic steering performances of the 4f resonator were found to be 158 x 130 resolved directions with a moving pinhole inside the cavity. 28 x 22 resolved directions were obtained with the OA SLM programmable aperture. Beam steering efficiency was 50% and response time was 40 ms.

These results demonstrate, for the first time to our knowledge, the proof of concept of the 4f resonator with a  $\mu$ PDLC based OA SLM, for intra-cavity beam steering.

- 2) **The Fourier Transform Optical Parametric Amplifier (FT-OPO)** concept allows to convert a deflected beam at 1  $\mu\text{m}$  into a deflected beam at longer wavelengths by means of an OPO. Nonlinear crystals used as OPOs usually possess a very low acceptance angle. Hence a specially designed OPO is required to convert the deflected pump beam, the so-called FT-OPO patented by THALES R&T. The basic idea is to convert a deflection into a displacement. The nonlinear crystal is placed in the focal planes of two lenses. Thus the deflected pump beam at 1  $\mu\text{m}$  enters the nonlinear crystal at the same incident angle whatever the initial beam direction, allowing optimised wavelength conversion. The second lens allows to re-deflect the converted beam.

The FT-OPO architecture was chosen based on a trade off between pump energy, number of resolved points and size of the OPO crystal, as a result of the theoretical study of beam propagation inside the FT-OPO and sizes of the pump (1  $\mu\text{m}$ ), signal (1.5  $\mu\text{m}$ ) and idler (3.5  $\mu\text{m}$ ) beams. The constructed OPO was formed by an x-cut KTA crystal. The crystal was inserted inside a linear cavity.

Regarding the deflection device, one of the main advantages of this scheme is that the BSD is operating at 1  $\mu\text{m}$ . Therefore highly efficient, reliable commercial BSD can be used. For the ATLAS demonstration, an acousto-optic device from AA Optoelectronic was used for extra-cavity steering.

Beam steering was demonstrated at 1.5  $\mu\text{m}$  and 3.5  $\mu\text{m}$ , with excellent beam quality at 3.5  $\mu\text{m}$ , about 50 resolved points in each direction for both wavelengths and almost constant pulse energies on the full deflection range. The beam steering efficiency of the BSD at 1  $\mu\text{m}$  was 53%, the OPO efficiency was 29% at 1.5  $\mu\text{m}$  and 5.3% at 3.5  $\mu\text{m}$ , leading to an overall efficiency of 15% at 1.5  $\mu\text{m}$  and 2.8% at 3.5  $\mu\text{m}$ . The response time of the device was 10  $\mu\text{s}$ .

In addition, efficient multitarget designation was demonstrated at both wavelengths with simultaneous generation of several beams.

## 2.5 ENGINEERING STUDIES

Based on some selected experimental BSD demonstrations performed during the project, theoretical studies were performed by Galileo Avionica to address airborne architecture and system performances.

- 1) A **theoretical design study for an airborne architecture** was proposed for an optical device performing beam steering at 1  $\mu\text{m}$  and the wavelength conversion with the FT-OPO system. A folded optical configuration was studied, in order to make the unit as compact as possible. With the commercial acousto-optic deflector produced by AA Optoelectronic for performing the beam steering at 1  $\mu\text{m}$ , an opto-mechanical architecture was derived, based on criteria like compactness, low weight and resistance to thermal variations and vibration loads. Even if no thermo-structural analysis was performed in the context of this work, design choices like optical path, structure shape, mechanical supports configuration,

thermal dissipation criteria and optical alignment criteria were based on industrial experience in the field of electro-optical avionic equipments.

The result of the study was an opto-mechanical lay-out in which the optical components inside the housing are mounted on both faces of an intermediate plate in such a way that the optical path is folded on both faces and from the upper plane to the lower one. A preliminary list of interfaces was issued, that could be considered as the starting point of a possible future activity of design and analysis aimed at realizing this optical device.

- 2) The scope of the **System level simulations** was to elaborate the modelling methods and a numerical study for airborne applications featuring a beam steering device at 1.5  $\mu\text{m}$ . Models have been implemented for several fine and coarse beam steering devices : PLZT and PMN-PT prisms, PMN-PT phased array and micro-lens arrays, using the measured parameters and also extrapolated beam efficiency for the combined C/F BSD. The models accounted for : transmitter/receiver optics transmittance and aperture; BSD device transmittance and response times; laser pulse peak power, duration and repetition frequency; receiver frame rate, field of view, shot, thermal and sky background noise; superposition areas of the transmitter solid angle and the receiver field-of-view; atmosphere extinction. Hypotheses of system parameters corresponding to typical operational systems were chosen, with both monostatic and bistatic Tx-Rx configurations. Target models were taken as NATO standard target (2.3x2.3  $\text{m}^2$ ), 7x4  $\text{m}^2$  extended target and 10 mm diameter cable.

Numerical simulations clearly showed that for the three investigated applications (OWS, Active Imaging and Range Finding/Designator), the configuration of PMN-PT phased array + MLA and bistatic Tx-Rx obtains the best performance in terms of target Fill Factor (FF), average detection probability and Probability Fill Factor parameter (PFF), defined as the fraction of scanning points whose detection probability exceeds 0.999. Hence this promising configuration has also been simulated with extrapolated beam efficiency, based on the proposed basic PMN-PT device improvements (AR coating, light coupling through the phased array with two fixed cylindrical micro-lens arrays), with following results :

- In OWS with NATO targets, range was extended from 500 m to 700 m using the same other system parameters, bistatic configuration and with 100 kW laser peak power, obtaining Fill Factor FF=0.10 and Probability Fill Factor PFF=0.96.
- In Active Imaging with NATO targets, 1000 m range was feasible with 25 kW laser power instead of 75 kW. 1500 m range was also possible with 100 kW laser peak power, for both bistatic and monostatic cases.
- In Range Finding with extended targets, using 10 MW, 5 ns laser pulses and bistatic configuration, the obtained range was 21 km when atmosphere visibility was 25 km, and was reduced to 13 km with 10 km visibility.

DIRCM application was investigated considering the FT-OPO concept and a generalized beam steering device with a given output power, beam divergence and scanning field of view.

In Active Tracking operations at pulse repetition frequency of 10 kHz, energy per pulse of 100  $\mu\text{J}$  at the transmitter output and at 3.9  $\mu\text{m}$  wavelength, a range of 6 to 7 km was obtained with 10 to 25 km visibility. At 2.0  $\mu\text{m}$ , range was reduced to 5.5 to 6.5 km. When pulse repetition frequency was increased to 30 kHz and energy/pulse was reduced to 30  $\mu\text{J}$ , obtained ranges at 3.9  $\mu\text{m}$  were 4.8 km and 5.3 km with visibility of 10 and 25 km respectively; at 2.0  $\mu\text{m}$  ranges were reduced to 4.4 and 5.1 km.

In Jamming operation, the pulse repetition frequency was raised to 100 kHz and the emitted pulse energy was 10  $\mu\text{J}$ ; it resulted at 2.0  $\mu\text{m}$  wavelength that jamming ranges were 15 to 25 km for visibilities of 10 to 25 km respectively; ranges were higher than those evaluated for active tracking operations at 2.0  $\mu\text{m}$  wavelength. At 3.9  $\mu\text{m}$  wavelength, feasible ranges of 20 to 29 km were obtained for visibilities of 10 to 25 km; also in this case ranges were higher than those evaluated for active tracking operations at 3.9  $\mu\text{m}$  wavelength.

### 3 READINESS LEVELS AND APPLICABILITY OF TECHNOLOGIES

A Technology Readiness Level (TRL) assessment was performed for the demonstrated components based on the simulated and measured performances. All ATLAS investigated technologies were demonstrated to be TRL 4, except for PDLC which are less mature materials and lead to TRL 3 for PDLC based devices.

Next development steps have been identified and proposed to increase the TRLs of the devices :

- For the fine BSDs, realization of 2D beam steering phased arrays, improvement of the steering efficiency by AR coating and light coupling through the phased array with two fixed cylindrical MLAs;
- For the coarse BSD, integration of the MLAs in a suitable piezo actuator for dynamic steering, testing of grey-tone lithography produced MLAs, design improvement as a function of the wavelength;
- For the combined Coarse / Fine BSD, realization of a 2D device, elimination of the imaging lens and combination of the efficiency optimized FSD with a fully developed piezo-driven coarse BSD;
- For the intra-cavity steering, use of a higher transmission light valve in the non diffusive regime (ON region) to increase the output energy, demonstration of ns pulses to use the intra-cavity beam steering laser in conjunction with the FT-OPO, and test of the laser under environmental conditions.
- For the Fourier Transform OPO, realization of a prototype according to the engineering model proposed and test of the breadboard in environmental conditions.

The successful demonstrations in laboratory environment allowed to evaluate the technologies capabilities and applicability regarding the envisaged applications. Major conclusions are as follows :

- (i) For multi-target designation, all the developed technologies can fulfil the response time requirement, but only the combined coarse/fine BSD can provide the required number of resolved directions.
- (ii) For fast continuous scanning, only fast technologies are suited, based on EO ceramics, with intrinsic response time in the  $\mu\text{s}$  range, or the FT-OPO with  $10\mu\text{s}$  response time. Only the EO phased array can provide the required number of resolved directions, also the FT-OPO in a lesser extent.
- (iii) For active fine tracking, the key issue is the spectral range of 2 to  $5\mu\text{m}$ . Only the FT-OPO can operate simultaneously at several wavelengths (same scanning angle for pump, signal and idler). If one single wavelength is required, both EO ceramic phased array and FT-OPO technologies are very well suited. The MLAs are also interesting, yet a little bit slow. It has to be pointed out that the FT-OPO completely fulfils the application requirements, even regarding the required output energy.

### 4 CONCLUSIONS - RECOMMENDATIONS

During the ATLAS project, several technologies for non-mechanical laser beam steering have been developed and successfully tested. Some of the results are particularly interesting and promising, such as :

- The combined Coarse/Fine BSD at  $1.5\mu\text{m}$ , for which the successful tests are a major step toward a quasi non-mechanical BSD for agile, continuous and high resolution laser beam steering.
- The Fourier Transform OPO concept, which is very well suited for active fine tracking and can be of great interest as efficient COTS electro-optic and acousto-optic BSDs already exist at  $1\mu\text{m}$ .

As a result of the above analysis, the technologies that should be pushed forward for future work in an ATLAS follow-on are the combined coarse/fine BSD, including the optical phased array, and the FT-OPO. Solutions have been identified to bring these technologies to a higher TRL. In particular :

- free space architectures for compact and efficient 2D optical phased array and combined coarse/fine BSD are proposed. A particularly interesting fiber based combined architecture is also proposed.
- The identified steps to increase the TRL of the FT-OPO are the realization of a prototype according to the proposed airborne architecture, and the test of the breadboard in environmental conditions.

Provided this further work, the TRL for both technologies is expected to increase to TRL 5 to 6.