CASAM - WP110

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PUBLISHABLE FINAL ACTIVITY REPORT

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This document summarises the project activities and results over the full duration from June 1st, 2006 till end of the project on June 30, 2009

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Document manager	Jean-Pascal MARTINENQ	SAGEM

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Table of Contents

1. CASAM PRESENTATION

1.1. REMINDER OF THE CONTEXT

Security has been a major issue for commercial air transport for many decades, as terrorist attacks on commercial aircraft have a big psychological impact on population, and thus on economical activity.

Beside the 11th of September twin towers type of event exists another threat: 15,000 disseminated shoulder launched IR guided missiles (MANPADS) which are in uncontrolled hands. Several attacks already occurred and evidence of traffic has been reported, as MANPADS are plentiful on the black market, inexpensive and easy to operate.

The US are preparing some regulations to force commercial aircraft to be equipped with onboard protection systems. It is vital for Europe from a security and an economical point of view to be able to answer this requirement as well.

A protection system is made of a missile detector and of defeating equipment. The EU project CASAM (Civil Aircraft Security Against MANPADS) concentrates research on the defeating equipment, which is considered to be that part of an aircraft’s protection system which has substantial cost and weight: an innovative Directed Infra Red Countermeasure (DIRCM) equipment shall be specifically designed for commercial aircraft, bringing minimum perturbation on the aircraft operation and the airport environment.

Hence the global objective of CASAM project is to design and validate a laser-based DIRCM module for MANPADS jamming, which will comply with the constraints of commercial air transportation, including the civil aircraft profile of flight, and will be able to defeat MANPADS of first and second generation (currently the most available world-wide) and also of third generation which may become a threat in the future.

Through a three-year project, CASAM explores several technological breakthroughs in laser, optics, electro mechanics and processing that will be the core of the future competitive equipment. Specific effort is put on threat analysis and simulation, economical analysis, aircraft installation constraints and impact. A specific study is being carried out on legal and regulation issues which have a prominent position in the roadmap.

Major European actors (large enterprises and Research organisations) and highly specialised SMEs cooperate inside a Consortium, bringing all skills and resources necessary to make CASAM a success and reinforce the European position in this domain.

1.2. EVOLUTION OF OBJECTIVES OF THE ORIGINAL PROPOSAL

The four amendment proposed and accepted during the project life were concerning repartitions and budgets of tasks inside the share of work and were reporting some project duration extension (from two to three years).

The main reason of duration extension is that we have experienced some wider and more complex tasks than expected to architecture, design, detail design, manufacture and assemble the demonstrator which constitutes one of the key results of the project.

The success of final live demonstration has shown the pertinence of those amendments and the quality of the work done to design and built this demonstrator.

As far as the dissemination actions are concerned, confidentiality rules around DIRCM activities (technical and commercial) did not allow a full completion of the related WP.

Nevertheless, slides presented during the Final meeting on 25/06/2009 in Röthenbach have been distributed as “Publishable” documents and Consortium partners were encouraged to continue their own dissemination actions after the end of CASAM project.

1.3. STRUCTURE OF THE DOCUMENT

After a detailed reminder of the CASAM objectives (chapter 2, based on contractual Description of Work), this document is structured around CASAM main aspects:

- Threats assessment and scenarios,
- System architecture,
- Demonstrator,
- Flight protection,
- Legal issues,
- Economics studies,
- Technology breakthrough.

For each of those topics, a summary of performed activities is given and the main achievements are underlined.

2. CASAM PROJECT OBJECTIVES

Extracts from contractual Annex I: "Description of work".

2.1. NEEDS AND ISSUES

Security has been a major issue for commercial air transport for many decades. The events of September 11th highlighted the need for improved security on-board aircraft. Systems are now being developed to reduce the likelihood of physical and / or electronic hijacking. Also, on-board security is likely to include a system by which ground based **m**an-**p**ortable **a**ir **d**efence **s**ystems (missiles, known as MANPADS) can be defeated. Infra-red (IR) MANPADS are guided weapons which are plentiful on the black market, inexpensive and easy to operate. As a result they are one of the terrorists' weapons of choice for attacking aircraft.

Terrorists Attacks

On November 28, 2002, terrorists linked to Al-Qaeda fired two SA-7 MANPADS in an attempt to shoot down an Israeli jetliner taking off from Mombassa, Kenya; this attack failed but has been followed by other attacks, particularly in Iraq. Another attack was launched in 2003 against a DHL aircraft in Baghdad. Increased security in respect of passengers has meant that terrorists must look elsewhere to attack. Taking into account the large number of MANPADS currently known to be in possession of over 27 terrorists groups, their relatively low cost, and the vulnerability of large aircraft on landing or taking off, the probability of such attacks appears to be high.

Commercial Aircraft Vulnerability

The vulnerability of commercial aircraft can be illustrated by traffic at London Heathrow Airport (LHR). LHR has some 480,000 aircraft movement per year; at peak times up to 120 movements per hour are routinely accommodated; taking into account the flight-paths and MANPADS characteristics, there may be up to 60 aircraft at risk of attack at any one time within an area of about 800 square km's around LHR. A supplementary area of 5000 square km's surrounding the airport exhibits a low to medium risk of successful terrorist MANPADS attack. The size of the area presents a significant risk of ground attacks which are difficult to prevent using existing ground countermeasures. However, the airports presenting higher risks (to fly in to and out of) are often located in other jurisdictions (for example middle east) which may not be willing or able to set up adequate measures against terrorists.

As a result, any defence against MANPADS attacks should include a mix of ground based measures and/or on-board counter-measure systems, which have been developed for the commercial aircraft environment.

General Defence Requirements

The flight duration of a light-weight - man-portable surface-to-air missiles (SAM), before hitting an aircraft, is often less than ten seconds. In that time, a defence system must first detect and locate the missile, and then initiate action to make the missile miss the aircraft. The likely scenario is that a terrorist would fire more than one missile to increase their chance of success. As a result, any commercial aircraft defence system should be able to counter at least two missile attacks.

On-board defence technologies against surface-to-air (SAM) and air-to-air missiles (AAM) have been developed for military aircraft for many years. But the existing military defence systems cannot be migrated to commercial aircraft without significant development. This is because they do not fit the specific characteristics of civil transport aircraft and are expensive. Some of the main differences between military and civilian aircraft are the size of the aircraft, the design of the engines which have quite different size and thermal signatures, in-flight long range and high altitude trajectories, on average 2 to 5 take-off or landing per day, the operational and economic needs of airlines (acquisition cost, flight hours, block times, maintenance, reliability, MTBF, training, etc) and environmental constraints. The MANPADs used will be likely first or second generation systems and will be aimed at aircrafts flying below 15 000 feet and lower. The impact of the defence system on the ground-structures and on the population must be reduced to effectively zero.

US Homeland Security Activities and EU-Constraints

The US Department of Homeland Security (DHS) has launched a two-year programme (with funding close to USD 100 Million) in August 2004 to develop, test, and certify a suitable system for commercial aircraft. It is considered probable (a bill is already under consideration) that, if successful, this programme will result in US legislation to mandate the installation of counter-measures (Directed IR Counter Measure, DIRCM) onto all commercial aircraft that enter US air-space. Any international airline, and aircraft manufacturer will therefore have to comply with it. Obviously, if a single nation has the exclusivity of producing such a countermeasures device, the risk of distortions in competition would be considerable. Another likely consequence is that the DHS may proceed to set the standards and rules - without reference to the EC and EU-community.

There is therefore a strong and urgent need for European research programmes investigating on-board counter measures systems tailored to the specific needs and constraints of commercial airlines.

2.2. QUALIFIED SPECIFIC OBJECTIVES

Other proposals, e.g. within the Preliminary Action for Security Research (PASR) or by the Israeli Airline “EL-AL” are dealing with ground protection systems in the vicinity of airports and general issues of on-board self protection (missile warning systems in combination with hot flares or intense IR-sources, etc.). It is clear now that the US is developing a DIRCM system and that such a system will probably be imposed through ad-hoc regulation. Such a system includes a Missile Warning System (MWS) and a laser-based DIRCM system. This laser-based DIRCM component with its powerful Laser and its sophisticated laser beam director is the most difficult part of this comprehensive system.

The global objective of the proposed CASAM project (Civil Aircraft Security Against MANPADS project), is to design, and validate a closed-loop laser-based DIRCM (Directed IR-Counter Measure) module for MANPADS jamming, which will comply with the constraints of **commercial** air transportation, including the civil aircraft profile of flight, and will be able to defeat MANPADS of first and second generation (currently the most available world-wide) and also of third generation which may be available in the future. It is the CASAM team’s understanding that the DHS is not developing a system specific to commercial aviation but rather attempting to merely adapt existing military systems. CASAM do not consider that this approach, in the long term, will benefit commercial aviation because military systems are not designed with reference to the specific requirements and constraints relevant to commercial aviation.

The detailed CASAM objectives include:

- Taking into account relevant regulation and standardisation issues, to define, with the end-users the consolidated operational requirements for commercial airliners (e.g. the total ownership cost per hour of flight) and the resulting specific technical requirements / specification for the DIRCM;

- To define the detailed architecture of critical subsystems (turret, opto-mechanical unit, laser and related software) of a closed-loop DIRCM-system able to detect a threatening MANPAD threat, to identify the type of IR-seeker, to track the missile and to jam the MANPAD-seeker within few seconds.

- To design and demonstrate an innovative and simplified turret exhibiting:
  - full spatial coverage with two turrets
  - high agility: 90° rotation within 100 ms
  - use composite materials, so that the system will have low drag (externally exposed volume below 3 litres) and low weight (below 3 kg) for the mobile part
  - passive and active closed-loop tracking based on a multifunctional simplified sensor: angular field of view about 10°, detection of a missile in a ballistic flight, recognition of the type of the seeker of a MANPAD
  - The turret will be modular for allowing to incorporate future generations of Lasers.
- To design and demonstrate an innovative IR laser source: wavelength 1.8-5µm, with at least 2 band independently tuneable, high repetition rate, with controllable wave form in order to be used for both identification and defeating modes. This research will address short term and medium term threats by utilising :
  - A leading edge laboratory prototype to be included in the DIRCM laboratory prototype able to defeat current threat
  - Progress on promising technologies that could be used against future threats or that could bring significant breakthroughs in respect of mass, cost and power consumption.
- To design and demonstrate a DIRCM software (including controlling the turret, seeker identification, tracking, laser beam controlling, defeat signal) and an interface connecting an off-the-shelf Missile Warning System (MWS) and the DIRCM. The first software will be modular in order to allow incorporation of future generations of Lasers.
- Within national confidentiality/classification constraints, to validate on ground the DIRCM technology being developed. A simulation SW-model of MWS will be coupled to the laboratory prototype of the DIRCM and used to defeat a real missile-seeker;
- To determine the expected level of protection achievable by such a system, in particular in the high threat environment in close vicinity of airports;
- To evaluate the economic and regulatory impact of installing DIRCOM systems on commercial aircraft;
- To provide information to the European Commission and to European Governments in support of international negotiations dealing with MANPADS / protection of civil aircrafts against missiles (MSL).

All those CASAM objectives were achieved during the project as detailed in this document and in CASAM deliverables available on CASAM Web site.

2.3. CURRENT STATE OF THE ART

The Threat - Types of Shoulder-Fired SAMs

MANPAD missiles are most easily categorised by the type of guidance system employed. For practical purposes, there are in three basic types that could be considered to be applicable to this study, command line of sight, laser beam-rider and infra-red self-guided.

Command line-of-sight (CLOS) missiles do not home in on a particular aspect (heat source or radio- or radar transmissions) of the targeted aircraft. Instead, the missile operator or gunner visually acquires the target using a magnified optical sight and then uses radio remote controls to “fly” the missile into the aircraft. In order to be effective, the CLOS requires highly trained and skilled operators. Numerous reports from the Soviet-Afghan War (in the 1980s) cited Afghan Mujahidin as being disappointed with the British-supplied Blowpipe CLOS this was because it was too difficult to learn to use and was very inaccurate when deployed against fast moving jet aircraft. The CLOS missile is also not a “fire and forget” system; the operator is more vulnerable because he can be identified by the size of the firing device and the plume of smoke when fired.

Laser beam riding MANPADS use lasers to guide the missiles to the target. The missile literally flies along the laser beam and strikes the aircraft where the missile operator or gunner aims the laser. These beam riding missiles, such as Sweden’s RBS-70 and Britain’s Starstreak, are considered to be effectively resistant to current countermeasure systems on military and civilian aircraft. But such missiles also require relatively extensive training to become a skilled operator. Again they are not “fire and forget” and not really hidden.

Given these considerations, many experts believe that CLOS and laser beam-rider missiles are not ideally suited for terrorist use. The more advanced types of CLOS missiles in particular are less freely available to terrorist organisations on the weapons market. **For this reason the study will concentrate on the IR-guided SAMs**, which - have been identified by various unclassified published sources - are being far more readily available to terrorist organisations (500,000 IR guided SAMs produced worldwide, at least 15,000 being disseminated and out of control), and have already been used to target commercial aircraft.

Infra-red (IR) guided missiles are “fire and forget” missiles and are designed to lock onto a heat source on an aircraft, typically either the prop- or turbine engine or its exhaust plumes, and to detonate a warhead in or near the heat source in order to disable the aircraft.

These IR-missiles use passive guidance, meaning that they do not emit signals to detect a heat source, which makes them difficult to be detected by targeted aircraft employing countermeasure systems. The first of these missiles was deployed in the 1960s. Technology of the seeker head is the main difference between generations of “fire and forget” IR MANPADs.

- **First generation** shoulder-fired SAMs such as the U.S. Redeye, early versions of the Soviet SA-7, and the Chinese HN-5 are considered “tail chase weapons”, as their seekers are reliant on un-cooled short-waveband (1-2.4µm) detectors and utilise **simple guidance processes**. In general, these can only acquire and engage an aircraft after it has passed the missile’s firing position, when the rear-side (hot metal) of the aircraft’s engines are fully exposed to the missile’s seeker. Such first generation IR-missiles are also highly susceptible to interfering thermal signatures from background sources, including the sun, which can significantly reduce the overall missile effectiveness. For example, it is believed that the Mombassa attack failed because the seeker became blinded by the sun reflecting off the wing and flew past the aircraft as a result. These missiles use seekers based on amplitude modulation with rather simple electronics. The aircraft IR hot source can be located in polar co-ordinates (discrete control for radius and proportional control for angle) with a modulation wheel.

- **Second generation** IR missiles, such as early versions of the U.S. Stinger, the Soviet SA-14, and the Chinese FN-6, use liquid nitrogen cooled PbSe or InSb detectors (wavelength 3-5&1-2.4µm, i.e. the wavelength of maximum radiation spectrum of an operating engine) and improved guidance techniques within the seeker head which enables the seeker to filter out most interfering background IR sources, as well as enabling head-on and side engagement profiles. Due to their low energetic yield, they need much energy. **These missiles also employ technologies to counter decoy flare** that might be deployed by targeted aircrafts. The seekers are also based on a modulation wheel which operates in frequency modulation to allow both radius and polar angle proportional control. Some of these seekers use a second UV spectral band for decoy rejection.

- **Third generation** IR shoulder-fired SAMs such as the French Mistral, the Russian SA-18, and the U.S. Stinger B use single or multiple L or cross detectors combined with nutation scanning to produce a quasi-image and locate the target in cartesian co-ordinates, and may utilise several wavebands in the IR allowing it to discriminate between the signature of an engine and flares. Both second and third generation SAMs use electromechanical scanning. This type of scanning, (like the ones of the two first generation systems) has a spatiotemporal equivalence **making it possible to confuse a SAM IR seeker with adequate light modulation**.

- Missiles such as the U.S. Sting B, the Russian SA 18 use single or multiple detectors for quasi-imaging detection. The so-called rosette scan is achieved with two rotating prisms (each of them having a specific rotation speed) that cover the field of regard of the seeker. The aircraft IR signature results in a different temporal pattern of detection depending on the location of the aircraft in the field of regard. Defeating these seekers, with flares, is made difficult by using a second UV spectral band for decoy identification as well as trajectory algorithms with digital signal processing.

- **Fourth generation** missiles such as the U.S. Stinger Block 2, and further missiles believed to be under development in Russia, Japan, France, Germany and Israel are expected to incorporate linear scanning or focal plane array and other advanced sensor guidance systems (trajectory algorithms), which will in turn permit engagement at greater ranges, and provide even more robust countermeasure rejection capabilities. Such missiles are not under production, and thanks to better control techniques, they are not expected to become readily available within the next two decades. It should be noted that fourth generation systems are designed to be air-to-air missiles, that is to say they will be fired from fighter aircraft. As a result it is only a remote possibility that such a system would actually come into terrorists hands.

Numerous unclassified studies have identified that many terrorist organisations are believed to have access to second and third generation Infra-red (IR) guided missiles. DIRCM technology is considered the most likely way to defeat these threats with specific reference on the development and use of focal plane arrays.

All previous generations of seekers employing various sorts of scanning technology can be deceived using less sophisticated laser modulations and moderate power because of the spatio temporal equivalence brought by the seeker heads scanning system. In order to successfully jam the focal plane array there will be a requirement to increase laser power by several orders of magnitude and with no specific modulation. CASAM are of the opinion that seeker deceiving systems are the best way to defeat the likely MANPAD threat over the next 20-25 years and will therefore concentrate on this area. In this regard CASAM will study modular architecture that will enable upgrades to new laser sources or modulations from time to time. Parallel research on laser source technology will also benefit to future products derived from CASAM.

Directed Laser Based Jammers

Recent advances in lasers have led to the development and employment of directed jamming systems that use lasers as the source of infra-red energy. Again, a number of systems are currently available, including LAIRCM, a development of the Northrop Grumman AN/AAQ 24(V) DIRCM Nemesis which incorporates an infra-red mid-waveband laser.

As per the directed lamp systems, the laser output may be modulated such as to interfere with the guidance signals generated within the seeker, causing either missile guidance perturbation or loss of track. The modulation is a series of jamming codes adapted to the threat library. The primary benefits in going to a laser-based solution are the ability, thanks to their very narrow beam, to generate much more jamming power on the seeker than lamp based systems, while providing better weight, size, cost, power consumption and reliability. But the current generation of military laser based systems provides figures that are not sufficiently attractive for use commercial airlines. But nevertheless such a technology appears to be promising and CASAM will concentrate on DIRCM technology.

In terms of achieving missile seeker defeat, the **amount of energy** that actually impinges on the seeker is one of the key parameters, along with the time - following missile launch - before jamming begins, and how well matched the laser beam and its modulation is directed to the guidance system of the approaching missile.

- Various programmes are currently underway both in Europe and the United States investigating the merits of "**closed loop tracking**". This technique uses retro-reflections of the jamming laser from the seeker optics to more accurately track the missile seeker. This in turn allows the laser beam to be narrowed, providing higher jamming powers to be aimed at the missile seeker without any increase in the source laser size, weight and power consumption. Several jamming sequences are used successively until the one works. This method results in a statistic increase of mean jamming duration because the code sequence is built from a library without any information on the attacking missile. There is an instantaneous kill’s assessment which allows to address several MANPADS almost simultaneously.
- A refinement of this technique is to use the retro-reflections to identify the type of seeker on the threatening missile (based on temporal modulation of laser reflection from seeker optics), which in turn allows the jamming modulations to be optically ideally matched to the seeker; it potentially results in the decrease of energy necessary to speed up the defeating process.
- In the case of multiple missile engagements, it is important to achieve missile defeat quickly. Higher laser powers coupled with matched modulations are one approach towards achieving this aim. Shorter response time for more effectiveness and shorter following missile capability. This approach is called a deception technique. **CASAM will concentrate on this innovative issue.**
- As laser powers can be substantially increased, the possibility of causing damage to the detector in the missile seeker becomes available, which is another route towards achieving rapid missile defeat. This approach is often referred to as “dazzling” or "blinding". In general though such lasers are larger, require more aircraft power and their use in an automatic system may well have safety implications around the aircraft environment which are unacceptable in commercial applications; **the technology developed in CASAM will be compatible with more powerful sources.**

2.4. TECHNOLOGICAL APPROACH, INNOVATION

The goal of the research is to progress on innovative technologies that will identify an efficient and competitive DIRCM-system for use on a commercial aircraft. Military research has shown that it is possible to get efficient jamming capability. **The interesting challenge and the possible risk are linked to the global requirements of airlines and air framers: low total volume, low drag, low mass, low power consumption, high reliability, low LCC and no risk on ground and during take-off and landing**. Part of the challenge lies in technologies improvement and simplification through an innovating approach: military technologies need to be revisited in order to meet the civil airliner requirements. The main technical DIRCM modules need innovative work:

- Optronics have to be low volume, low mass and low costs. Current opto-mechanical DIRCM architecture have to be fully rethought to lower external pointing parts (to reduce drag) and simplified especially for pointing and stabilisation architecture, as well as functional gathering . Opto-mechanical turret will reach outstanding performance in steering and stabilisation at an unreached performance to cost ratio and performance to mass ratio. New Focal Plane Array (imagery sensor) will integrate passive and active detection modes for improved passive and active tracking modes. Line of sight stabilisation will use innovating low cost devices.

- Laser technology will be based on new progress in OPO crystals with a simplified architecture that will be specially adapted to civilian aircraft need and to the considered threat. For pump laser, research will be focused on mass, volume and consumption reduction, as well as output power and Pulse rate frequency improvement. OPO research will deal with wavelength conversion stage optimisation, crystal choice, arrangement and optimisation.

- Laser technology will be based on new efficient approaches including fibber lasers and simpler frequency conversion modules (OPO), as well as directly emitting mid-infrared semiconductor lasers. Emphasis is put on compactness, efficiency, and reliability

- Tracking technology will be adapted and optimised in synergy with hardware development. No doubt that civil DIRCM efficiency and optimisation will depend on system analysis and global design. More over, tracking will have to face very specific signal in active mode, so that algorithm will be rethought and adapted to temporal Laser Cross Section of MANPADs’ IR seekers.

As one can see, the methodology will make use of the majors following means:

- innovative research in pump lasers, OPO, opto-mechanical turret, FPA sensors, tracking algorithm, identification process,

- functional implementation optimisation for each technical module,

- global design and specification as the barycentre of current technology, innovative opportunities and system needs.

The CASAM clearly does not aim at re-inventing the wheel, but to base innovative approach on an exhaustive state-of-the-art in order to propose the best compromise for civil aircraft DIRCM.

A general literature review will be made at the level of system analysis in Task 221 and each technological Work Package in WP300 will include at first some literature review

The technological approach is as follows:

- To define a system which efficiency is focused on MANPADS: fortunately they can be defeated with less laser power than other missiles which are not disseminated.
- To define a smart system that will make the most efficient use of the laser defeating power thus reducing volume, mass, cost, power consumption.
- To identify the missile (type of seeker) and use the adequate defeating strategy (closed-loop DIRCM, adapted jamming code),
- To have the best pointing accuracy thus reducing the beam divergence and the laser power
- To work on miniaturisation of devices such as :
    - An innovative multi-wave length tuneable laser source with reasonable cooling management,
    - A new pointing device with its sophisticated opto-mechanical architecture, made with composite materials which result in high precision, low weight/low drag. Three innovations are expected:
        - (i) opto-mechanical design and motorisation of the gyro-stabilised turret,
        - (ii) passive and active tracking with a single multifunctional component Focal Plane Array (FPA) sensor,
        - (iii) materials innovation (technology transfer)
- To develop a high speed piloting software (passive and active tracking loop, fine tuning loop, image processing, damage assessment, turret and laser system working modes)
- To continuously monitor the compliance of this research by reference to system, installation and economic analysis, and continuous analysis of regulation and standardisation requirements.

All those CASAM issued were addressed during the project as detailed in this document and in CASAM deliverables available on CASAM Web site.

3. THREATS ASSESSMENT AND SCENARIOS

3.1. THREATS IDENTIFICATION AND DESCRIPTION

The main objective of the threat analysis was to define the threat posed to civil aviation by use of Manpads and give key features of the problem.

A review of the most disseminated Manpads has been performed, giving evidence of the general features:

- All designs share a certain number of common technical specifications
- Key points of the Manpads concepts are the weight and size for easy transport and concealing, the short range (< 5 km) leading to short flight time, the ease of use, the efficiency demonstrated during conflicts, and the low black market price for early models.
- Weaknesses of the Manpads concepts are the operational limitations (aircraft altitude and operator training), the lower civilian aircraft IR Signature for which old versions of Manpads missiles have not been designed, and the relatively small size of warhead in comparison with large airplanes. The usual sensitivity of Manpads homing heads to countermeasures like flares is no longer a weakness as improvements (bi-color, additional UV channel) make the homing heads less sensitive to flares and as using flares combined with a violent change in flight direction is not relevant over built-up areas near an airport and for a civilian aircraft.

Manpads classification and the seeker performances have been reviewed. Manpad systems can be divided into three families with respect to their guidance system:

- The older ones are guided by Command by Line Of Sight, in this case the gunner has to keep the target in its optical device and the orders are given to the missile by a wired link. These missiles are mainly used for anti-tank and anti-helicopter missions.
- The second and most encountered family is infrared seeker guidance. In this case, the gunner has to designate the target and to make the seeker lock on to the target. Once it is fired, the missile is autonomous.
- The third family is Laser Beam Riding. In this case, the target is designated by a fire control unit and the missile is equipped with a laser spot tracker.

From these classes, the easiest to be operated and the most furtive systems are IR seeker missile. IR seeker performs a space to time transformation or image processing in order to localize the target position in the seeker Field Of View. They can be divided into four families described as follows:

- **First generation:** reticle scan with amplitude modulation. Installed on SA-7, SA-9 Manpads, this seeker operates in the SWIR band and is very vulnerable to countermeasures. These missiles were used during Vietnam War and they have proved to be efficient against helicopters and slow flying aircraft.
- **Second generation:** reticle scan with frequency modulation. Installed on STINGER BASIC, this seeker uses cooled InSb detector which operates in MWIR band. It can perform CCM and has a better sensitivity.

- **Third generation:** pseudo imagery. Installed on STINGER POST, STINGER RMP, IRIS-T, the detector of this seeker is moving through a rosette pattern in order to cover the whole FOV. The obtained temporal signal is used to find the target coordinates with a good precision.

- **Fourth generation:** focal plane array (FPA). They use a line scanner or a FPA operating in MWIR or MWIR/SWIR spectral bands. There are fully digital seekers so they can perform efficient CCM. These seekers are reserved even today for few countries because they are still very expensive.

Seeker variants may include detection in IR-band 1 (2-3 μm), IR-band 2 (3-5 μm), or UV band.

The first and the second generations are the most commonly encountered. They represent more than 60% of the encounter probability. For these reasons, the potential threat for the project takes into account AM and FM reticule seeker.

As a result, two of the most disseminated Manpads have been selected to simulate generic threat. The first is the most disseminated Manpads: SA7. The second represents a new class of missile with enhanced capabilities which could be the future threat.

To be able to simulate the Manpads, a generic missile model has been realized. This model can simulate the two missiles depending on the numerical values used. They have been defined and tested first in an in-house simulation for validation and then transferred to WP230 for implementation on CASAM simulation.

The generic missile model simulates the behaviour of the typical Manpads during an interception. The model comprises four parts:

- Kinematics model
- Seeker model: to simulate ecartometry (magnitude of deviation from true alignment with the target) once given the instantaneous duel conditions.
- Flight phases
- Engagement sequence.

3.2. TYPICAL THREATS SCENARIOS

The scenarios form a set of conditions which were used for technology studies as well as conditions for performance evaluation. These scenarios consider two aircraft classes (turbojet and turboprop), two flight phases (take off and landing), for which flight profiles are given. An interception example performed with the in-house simulation is also given.

As previously mentioned, scenarios consider initial climb after takeoff and final approach before landing of civilian aircraft. During these flight phases, aircraft maneuverability is negligible.

Typical interception time is less than 10 seconds. In this interval, aircraft flight parameters are almost constant. So it is not needed to have a precise description of the flight phases for the scenarios.

A measurement campaign of civilian aircraft has been performed during this project and lead to an infrared signature database of several aircraft. Two typical aircraft, whose signature is available in the database, are considered in this project:

- Medium range aircraft (A320) with a low takeoff speed and an assumed reduced IR signature.
- Turboprop aircraft (ATR72) for another typical engine.

For WP230, the input parameters for target models during initial climb will be:

- True Air Speed wrt target time of flight - one dimension table
- Vertical Speed wrt target time of flight - one dimension table
- Altitude (from the ground) wrt target time of flight - one dimension table
- Horizontal distance from takeoff point wrt target time of flight - one dimension table
- Fuel flow as thrust level information wrt target time of flight - one dimension table - to be correlated later with IR signature

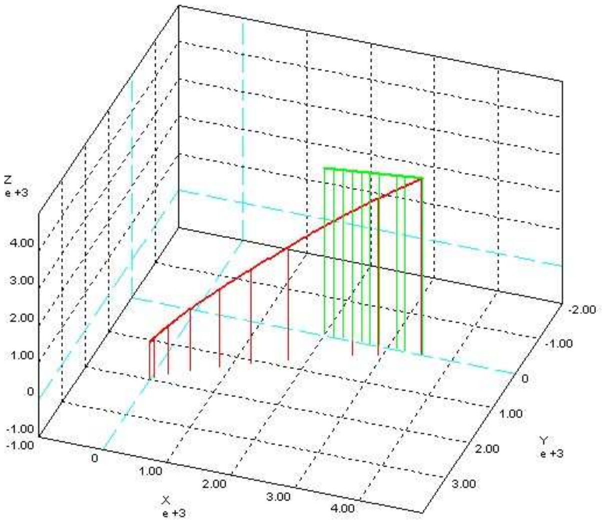
For WP230, the input parameters for target models during landing will be:

- True Air Speed wrt target time of flight during landing phase - one dimension table
- Vertical Speed wrt target time of flight during landing phase - one dimension table
- Altitude (from the ground) wrt target time of flight during landing phase - one dimension table
- Horizontal distance from landing point wrt target time of flight during landing phase - one dimension table
- Fuel flow as thrust level information wrt target time of flight during landing phase - one dimension table - to be correlated later with IR signature

The typical scenario is relative to a duel between a Manpad and an aircraft. These kind of scenario has been performed with an in house simulation only to show that target and missile models have been validated.

The figure shows a 3D representation of the interception.

- The colour for the target is green
- The colour for the missile is read



All models have been implemented in CASAM simulation. A brief evaluation of number of scenarios required for the project according to the sensitive parameters can be declined as followed:

- Missile
  - 2 generic missiles
  - 2 attacks (One missile attack and two missiles attack)
- Target
  - 3 aircraft
  - 2 two flight phases
- initial missile and target locations
  - n_T target locations wrt earth for each flight phases (at least 3)
  - n_C missile locations wrt earth for each engagement sequence (at least 9)
    - 3 initial distances to target
    - 3 angular locations wrt to target
- miscellaneous (additional parameters which can affect the trajectories)
  - n_W : number of weather conditions
  - n_{MWS} : number of MWS conditions
  - n_{DIRCM}: number of DIRCM conditions

Thus, an estimation of the number of scenarios required for the project is at least: $648^* n_W^* n_{MWS}^* n_{DIRCM}$

3.3. USER AND SYSTEM REQUIREMENTS CAPTURE

In an analysis of the current state-of-the-art of aircraft self-protection systems DIRCM showed up as the most promising, sustainable and best adapted system for civilian aircraft protection. But DIRCM commercialisation requires tightly integrated systems engineering and development, as well as testing and evaluation of existing and emerging military equipment. So efforts to transition DIRCM systems to civilian use face several limitations. The special requirements of a civilian user would be:

- achieving an affordable total cost of ownership;
- improving reliability over their military counterparts;
- performing less labour and time-intensive maintenance interventions;
- decreasing false alarm rates;
- *ensuring that these devices can be safely applied in operating environments of civilian aircraft.*

In order to meet civilian user needs CASAM provides an adapted list of system requirements including general necessities for the protection of an aircraft.

The time budget of the DIRCM to missile engagement process, which is affected by detection and designation of missile launch, verification time, pointing agility, in general, system responsiveness, shall be such, that a missile launch from a certain distance can be successful countered with a high probability. At all phases of engagement, pointing, which is affected by pointing accuracy, pointing stability, and laser beam parameters, shall be that accurate, to allow an adequate irradiance at the seeker.

Jamming performance, which is depending on available countermeasure wavelengths, the Jam-to-Signal ratio on these countermeasure wavelengths, and the jamming countermeasure technique, shall be such, that missiles contained in the threat scenario will be defeated with a high probability.

The size and weight of all components of the system shall be minimised as far as possible for ease of handling.

3.4. PRELIMINARY DIRCM SYSTEM REQUIREMENT

The general user and system requirements were transferred into DIRCM system requirements. During the process of investigation two architectures remained, denominated as basic and enhanced version.

As an alternative to the integration of different LRUs into the aircraft, a pod solution with all DIRCM parts including the MAWS' integrated into a single enclosure has been investigated. The pod would have the advantage of easy (de-)mounting, facilitating maintenance and resulting in reduced off-time for the aircraft. Moreover angular coverage of the DIRCM could possibly be enhanced.

According to the necessities of the enhanced second architecture required system level functions have been identified. The investigation of these functions resulted in the definition of 76 requirements for the DIRCM system that cover all aspects from general system requirements, detailed system functions to maintenance and logistics. The analysis resulted in a DIRCM product specification and the associated Internal Interfaces Control Document

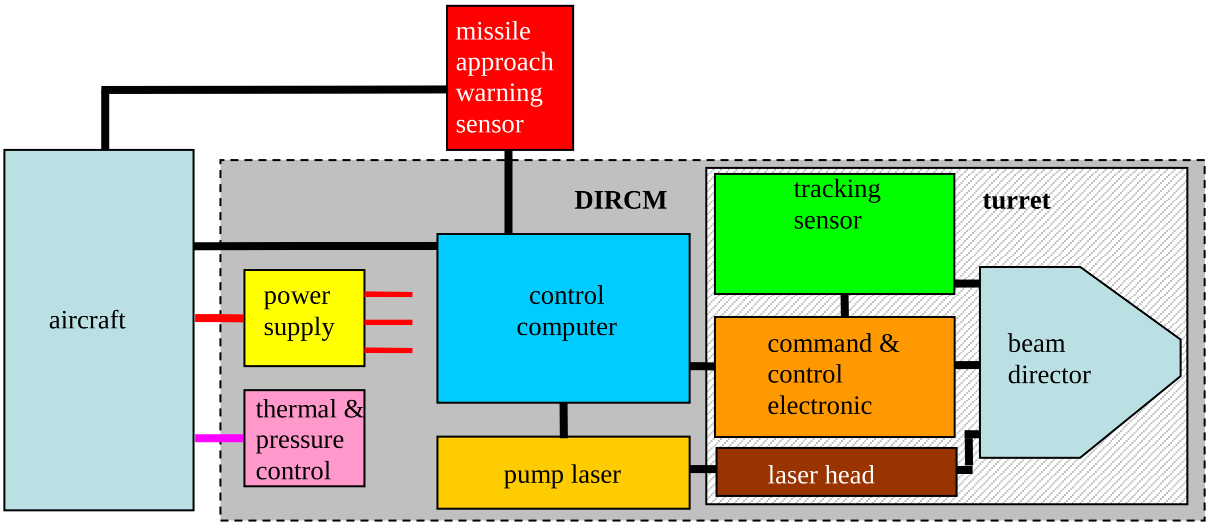
4. MAIN ACHIEVEMENTS

4.1. ANTI-MANPADS SYSTEM ARCHITECTURE BASED ON DIRCM REQUIREMENTS

The CASAM demonstrator as a future civil DIRCM system consists of some main modules, which are a passive IR sensor for target tracking, a jamming laser and a steering device. All DIRCM modules are computer controlled. The main modules are put together from several minor components. The DIRCM is connected to a MAWS. Some modules are integrated into a LRU like the turret, whereas other modules will be their own LRU.

LRU	module
turret	tracking sensor
	command & control electronic
	laser head
	beam director
control computer	control computer
pump laser	pump laser
power supply	power supply
thermal & pressure control	thermal & pressure control

As the physical size of the system has to be minimised, there is a strong need for small scale integration. Component design must take care of this requirement, an integral system approach has to be obeyed and mechanical interfaces could therefore be quite complex. In CASAM the modules belonging to the turret have been implemented according to this philosophy. The necessary computing devices have been realised on standard PC equipment and thermal & pressure control has not been implemented in the demonstrator device. An outline of the basic modules accompanied by a short description is given below, which reflects the enhanced architecture from the definition process. The turret as an own LRU is depicted with its main modules. The real physical structure of the DIRCM modules will be shown in the following chapters.



Beam director

The beam director is required for directing the optical axis of the DIRCM to the approaching missile. This must be done as fast as possible, taking into account the necessary accuracy. It includes a steering device. The size of the turret has been minimised in size to mitigate aerodynamic drawbacks. The turret is the only part of the DIRCM, which has an interface to the surrounding environment.

Tracking sensor

The tracking sensor gives an IR image of the threat with sufficient resolution to enable a computer by means of image processing to calculate precise threat position data in accordance with the laser divergence. The image processing computer is realised with a high performance standard PC computer.

Command and control electronics

This electronic gets position data input from the tracking sensor or the MAW, which is used to control the beam director. System command input is given by the DIRCM control computer.

Laser head

The laser shall jam the seeker of an approaching missile. It has a small beam divergence to maximise energy density but is large enough to allow for continuous target illumination. The laser wavelength must fit to the spectral transmission of current seekers. The laser head converts the pump radiation from the pump laser into the proper operating radiation.

Pump laser

The pump laser generates laser radiation out of electrical power. This pump radiation is delivered to the laser head by means of an optical fibre, to be converted into the required operating laser radiation.

DIRCM Control computer

The control computer is dedicated to several main tasks, which are:

- processing track sensor data
- control of system moding
- laser control including modulation
- interface module to the aircraft and to the MAWS

DIRCM Power supply

This power supply, where the source is the aircraft power, will deliver specific power needed by components of the DIRCM. For the demonstrator power is taken from the outside location.

Thermal and pressure control device

This device should contain means for thermal control of the DIRCM and allow for pressure adaptation. Electronics allowable temperature range must be guaranteed as well as the special needs of mechanical stabilisation of the optical axes within the turret. This module is not implemented in the demonstrator.

4.2. DIRCM DEMONSTRATOR

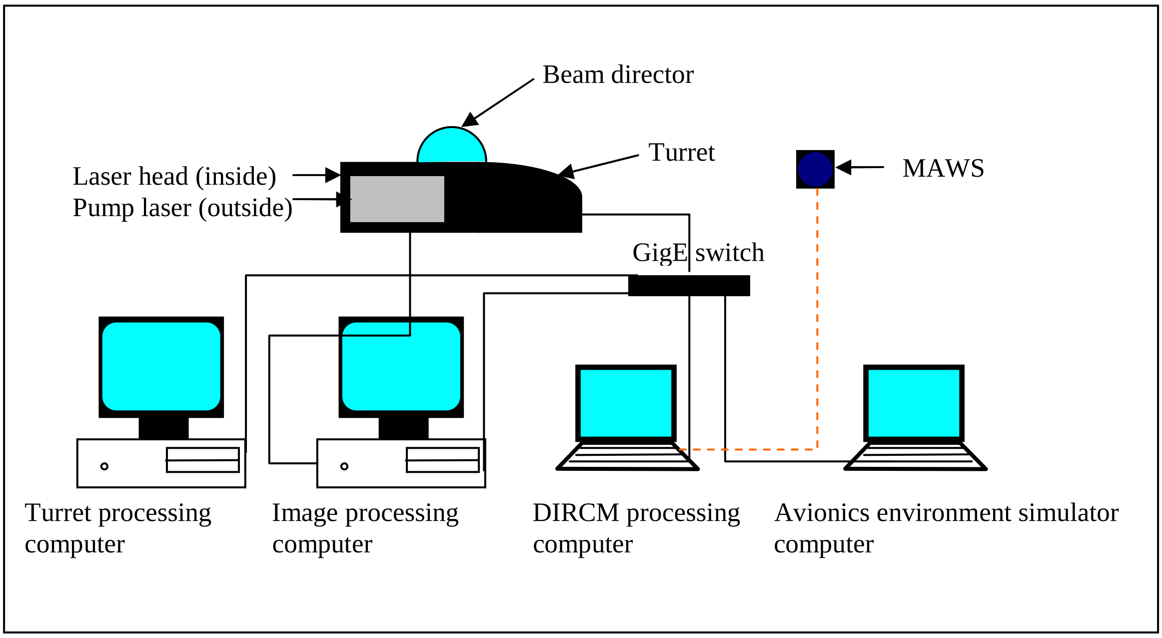
4.2.1. Description of the full demonstrator

4.2.1.1. Demonstrator breakdown

The CASAM demonstrator is based on the enhanced DIRCM architecture as shown in chapter 3.4 and incorporates all LRUs with exception of the thermal and pressure control, which is not necessary for ground test investigations. The main part of the DIRCM demonstrator is the turret comprising the steering mechanism, the passive tracking sensor and the laser head. Within the CASAM demonstrator major attempts were made to include new technology (piezoelectric motor) to come close to the objectives of realizing a compact and efficient system leading to a demonstrator of small size. The command and control electronics computer part (turret processing computer) has been implemented in a standard PC computer outside the chassis of the turret. The image processing unit as part of the tracking sensor is equally realized in a PC environment. Details of the turret can be found in chapter 4.2.1.2.

A small size fiber laser was used as pump laser for the wavelength converter (laser head). This device was located adjacent to the turret housing. Details of the laser can be found in chapter 4.2.1.3.2.1.

The DIRCM control computer has been implemented in a standard PC computer like all other computing devices. A connection to the MAWS was implemented. The avionics environment simulator constitutes the main operating device (the aircraft operating part), also implemented on a standard PC. Due to Gigabit-Ethernet connection these devices could be arranged for operation at distinct workplaces. The CASAM modules with exterior computing devices are depicted below.



4.2.1.2. Turret

4.2.1.2.1. High Agility compact turret

This task consisted in defining and manufacturing the optical, mechanical and electronic turret components allowing to build and evaluate the demonstrator by taking into account the needs and the functions defined for the demonstrator: compactness, passive and active tracking, identification, etc.

According to the project goals to have a DIRCM working in a closed-loop operation with a laser emitting in an IR dual-band, the optical design had to be defined in order to allow the laser beam emission and the passive IR reception signal recombination, while minimizing the optical losses on each optical path at the lowest level as possible. Several optical architectures had been studied and optimized before reaching an acceptable solution according to all our requirements.

Some internal laser reflections inside the system can lead to a total blindness of the sensor. The sensor sensitivity being very high for the tracking/identification performance we wanted to achieve, it can be saturated by only one weak reflection and thus being not able to duly perform its measurement task. . A complete simulation of the entire optical architecture with ray tracing was made so as to identify the critical reflections, and to eliminate them either by modifying the inclination of the surfaces, or by using screens and light traps.

Two other tasks decided during the project were :

- the design and realization of the “IF Truss”, mechanical structure intended for supporting the pump laser and the optical fibre. The creation of this structure was forced by the constraint to rigidly maintain the optical fibre appeared in the course of the project
- the addition of a monodector (MCT) with its associated optical architecture, in order to allow diagnosis in case of difficulty to comply with all the targeted functions of the MFPA (the most critical one being the modulation analysis capability)

All those tasks were achieved at the beginning of the trials.

4.2.1.2.2. Multi-functional Focal Plane Area (MFPA)

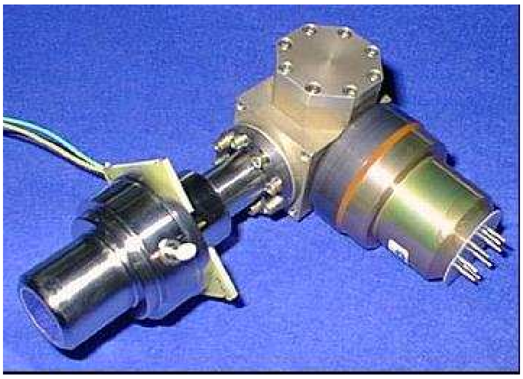
This task included the research activities to develop a highly performing multi-functional Focal Plane Array.

The choice of the FPA’s demonstrator features had been made in order to fulfill the system requirements. Thus, a frame rate > 4 kHz had to be obtained with a small size window of 16 x 32 pixels. We can also claim to have a very low ROIC noise. The window full frame size had been chosen for the best compromise between sensitivity and signal.

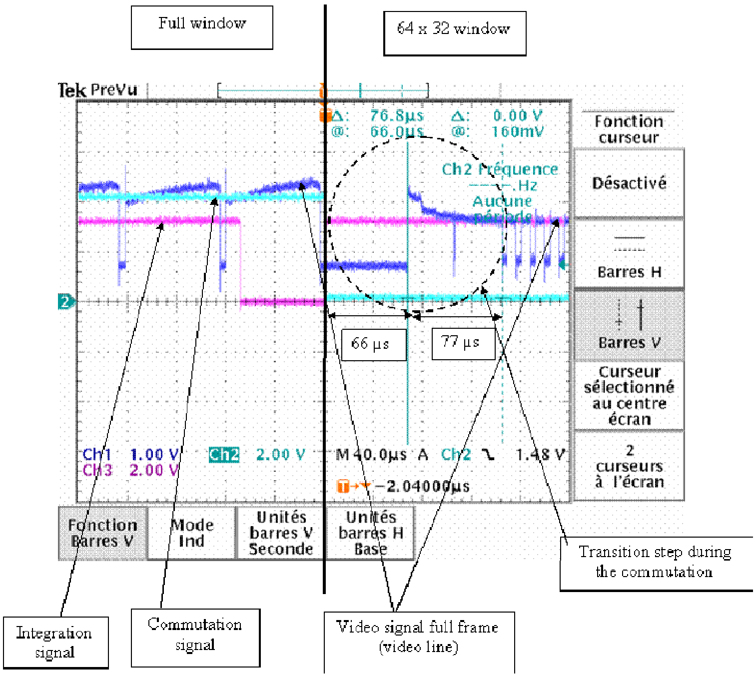
However, the switching time between large size window to small size window in a few frames only proved to be a requirement difficult to reach. Indeed, transition from the large size to the small size window was not commonplace. A special software development had been carried out to reduce this time, which can be about 1 to a few seconds if no precaution is taken. This capacity was developed and used successfully on the demonstrator.

The possibility to transmit data from the turret towards the DIRCM processing via an Ethernet Gigabits connection presents strong advantages: direct reading by a PC under Windows, line capacity to several hundred meters without loss. However, this exit format did not correspond to the current standard of the manufacturers which rather use the Camera link format. Conversion modules exist, but those were not compatible with switching time required for the DIRCM system.

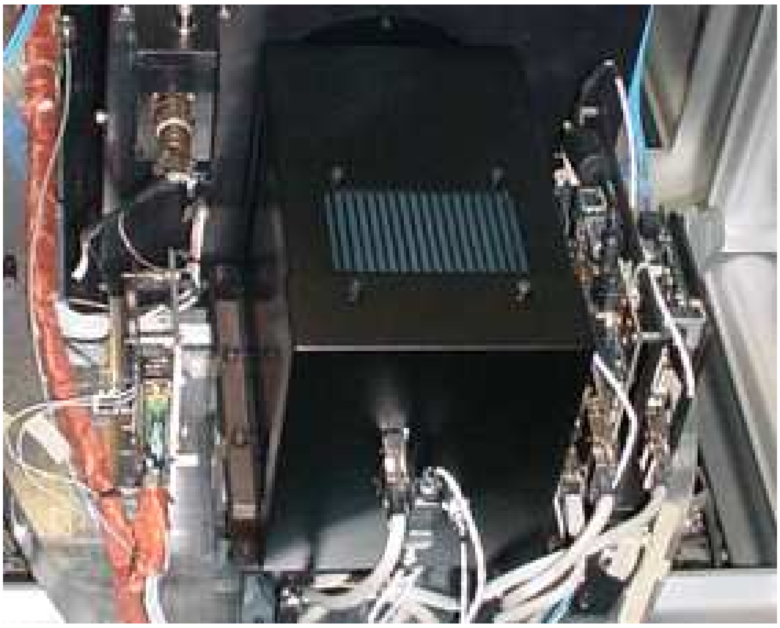
The following picture shows an InSb detector view:



The next diagram presents some of the numerous measurements made during the feasibility tests.



In the next picture, one can see the MFPA packaged and integrated inside the Optical Orientation Platform:



Please, refer also to § 4.4.4.2.

4.2.1.2.3. Ultra-Sonic Motors

This task included the research activities to develop a specific and adapted piezo-electric motorization for both turret axis (elevation and azimuth).

The available off-the-shelf Ultra-Sonic Motors (USM) did not cope with our stringent requirements for size, torque, speed and weight. Thus, based on this rather new technology, the development of second-new generation motors types was underway within the framework of the project. Most of the efforts were made on a “ring-like” high performance motor to drive the most constraining azimuth axis. Obtaining simultaneously the targeted speed and torque capabilities constitutes a technical challenge which required making several designs and then a progressive improvement process on the selected concept.

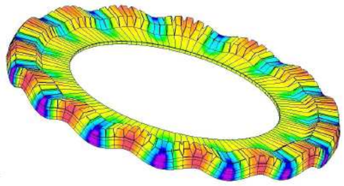
Several USM motor breadboards had been done and tested on a special test bench to choose the more suitable design for the azimuth motor. Targeted performance seemed to be on time achievable because the already recorded data are very promising. The choice for the elevation axis USM motor was less critical and remained close of a first generation USM motor available off the shelf.

Several types of prototypes were realized during the project.

The obtained performances were as high as the expectations as regards the torque and the speed, but an important work remains to make on the aspects of robustness and reliability. However, the objectives of evaluation of the project were widely reached as one of the prototypes was even taken up on the Turret used for the trials.

The next picture shows (at left) the simulated mode structure of an annular PZT structure similar to the one which has been used inside the steering head.

We can see also (at right) a view of the motor (stator and rotor) and of the electronics.



Please, refer also to § 4.4.4.1.

4.2.1.2.4. Composite materials

This task included the research activities to identify how to use composite materials at the maximum extent in order to reduce the weight and inertia of the mobile parts as well as other parts (according to their respective function) in order to save some weight on the full DIRCM system.

The use of composite materials had been examined for the turret fork and for the main cover of the upper part. To reduce the total weight of the turret, a composite structure could also be implemented to maintain optics in the low part of the turret.

The main cover and the cover of the steering turret were realized in carbon. The optical base plate, which is the optical bench of the Turret, had also to be realized in composite material. Regrettably, this bench arrived too late during the integration, and was replaced by an aluminum bench. The stability of this one was however sufficient to preserve the optical alignments during three months.

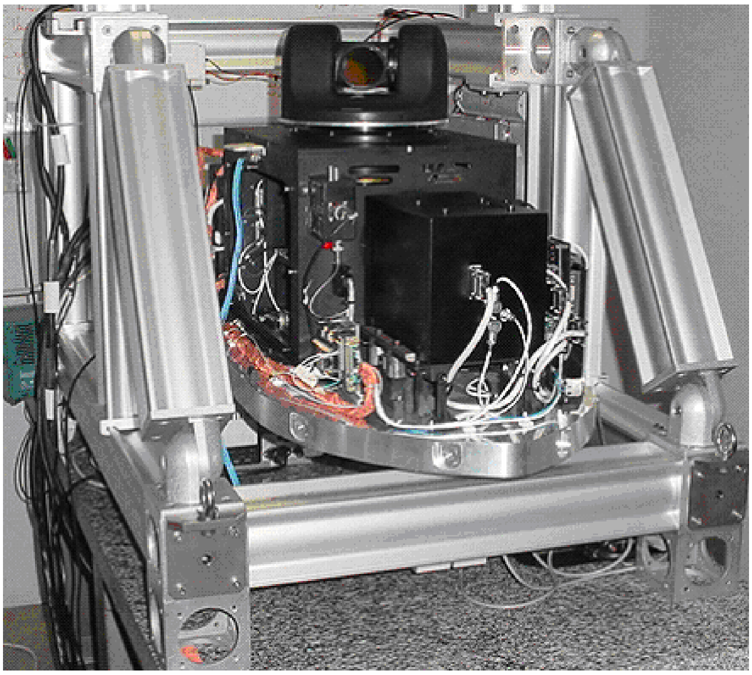
The next photos show views of the carbon composite covers:

Please, refer also to § 4.4.4.3.

4.2.1.2.5. Final assembly

The assembly and integration of the various internal and external equipments of the Turret, was the last task before the shipment of the Turret set up for integration with the other equipments of the demonstrator.

The following picture shows the Turret during the integration phase:



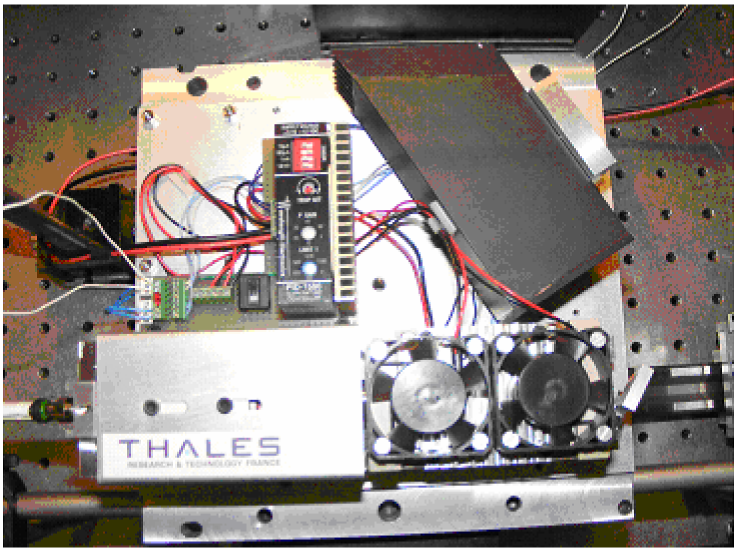
One can see in particular in the foreground the case containing the MFPA, as well as a part of the very complex cabling of the “Turret”

The photo shows also the “X” structure developed in order to support the pump laser and the fiber, taking into account the positioning of the Center of Gravity towards the rotary table axis, and the mechanical interface with this one.

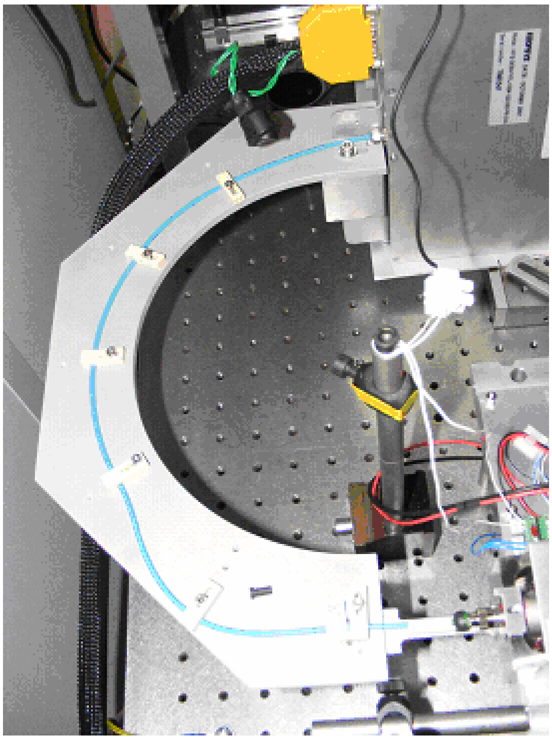
The optimization and characterization of the Turret involved more especially:

- MFPA adjustments and optimization (NUC, integration time, sensivity, attenuation, filtering,…)
- Reduction of the optical multi-reflections
- Beam paths alignments
- Reduction of electrical noises
- Integration of the OPO, and adjustments of the corresponding optical mirrors

The next picture shows the OPO finally integrated inside the Turret:



The optical fiber is shown hereafter, mounted on a metallic ledge fixed on the IF Truss structure:



The next picture shows a typical image of the target viewed by the MFPA through the optical system of the Turret.

We can see the rail (in diagonal considering the image rotation) as well as the hot spot (hot target) as a very brilliant point.

4.2.1.3. Laser source

4.2.1.3.1. Purpose and scope of the Laser Source Work Package

The CASAM project is investigating the feasibility and the validation of a Directed Infrared Countermeasure (DIRCM) equipment dedicated to the protection of commercial aircrafts against MANPADS.

A key component for the DIRCM system is the infrared laser source There was a need to develop and assess new mid-infrared laser source technologies with specifications matching those required for the project application, e.g., focusing on a compact and efficient laser with low cost of ownership.

The specificity of DIRCM laser sources is to emit several wavelengths in the 2 to 5 µm mid-infrared spectral range. The classical technological approach is to use mature diode-pumped 1µm solid-state lasers and frequency conversion stages (Optical Parametric Oscillators (OPO) modules) to access the required spectral range. However, two OPO modules are generally needed, which usually leads to complex optical arrangements and low overall efficiency of less than 2.5 %.

While such an approach has demonstrated the ability to deliver high average optical power, the CASAM application is requiring more compact and efficient solutions. For instance, the use of engineered non-linear materials like PPLN (Periodically Poled Lithium Niobate) allows more efficient frequency conversion and can yield simpler systems. Northrop Grumman has developed a compact DIRCM laser source based on a diode-pumped bulk crystal laser technology and PPLN for frequency conversion stages

The objectives of WP320 were twofold:

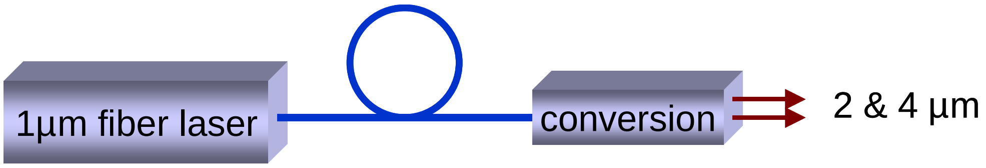
- To improve the current state of the art and deliver a prototype laser to the CASAM demonstrator
- To study new laser options at the laboratory level in order to roadmap future laser developments

The CASAM consortium has assumed a two-color mid-IR laser (typically 2 and 4 µm) with moderate average output power. Three different laser concepts have been studied, with potential for improved compactness, efficiency, and reliability.

- The first option is based on a 1 µm fibre laser pumped frequency conversion module. Fibre laser technology can yield more efficient and reliable devices than bulk lasers, while the frequency conversion module will integrate the two conversion stages in a single crystal. The expected gain is compactness and a factor of two in the electrical to optical efficiency (5%). The laser developed in this first option was to be packaged and delivered to the project for evaluation in the CASAM demonstrator.
- The second option focuses on using a fibre-based pump laser directly emitting in the 2 µm range. This radiation will be partly converted to the 3-5 µm range with a single conversion stage. The goal was to demonstrate the feasibility of 10 % electrical to optical efficiency.
- The last option concerns Quantum Cascade Lasers. These semiconductor lasers are extremely promising with respect to size and cost as compared to the other approaches but still require more research effort to fulfil the output power requirements in the 3-5 µm range. The objective was to demonstrate over 0.1 W of average power near room temperature with these devices and to devise a technological roadmap to higher power by the end of the project.

4.2.1.3.2. 1 µm fibre laser

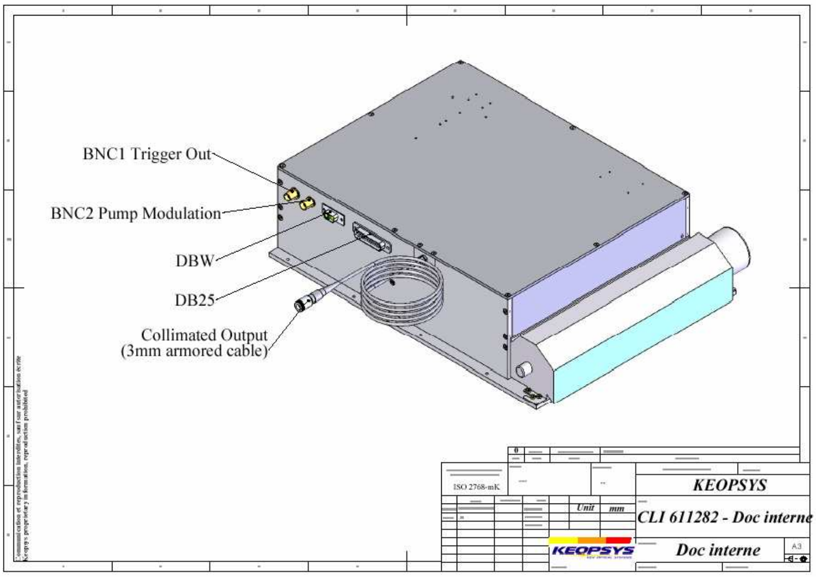
A two-color mid-IR laser source consisting of a 1 µm fiber laser pump and an OPO module was delivered to partners for the CASAM demonstrator. The 10 W polarized fiber laser emits 40 ns pulses at 40 kHz and is pumping an integrated two-stages frequency conversion module delivering Watt-level 2 µm and 4 µm near diffraction limited radiation with balanced power. Furthermore, the pulse train can be modulated with the required bandwidth for DIRCM processing. The figure below shows the principle of mid-IR generation using a 1 µm fiber laser pump. The frequency conversion module is to be inserted into the optical turret and is fiber coupled. The fiber laser pump was to be placed remotely from the optical turret.

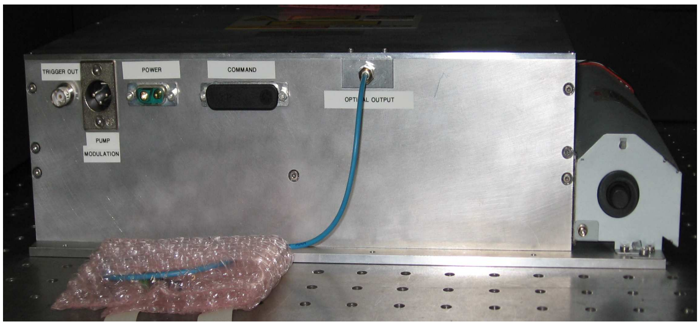


As for the fiber laser, all of the specifications were reached except the emission bandwidth which was slightly higher than targeted. This had some consequences on the OPO efficiency as all the emitted pump energy was not useful to the frequency conversion. It is however expected that this problem could be fixed with a small further development.

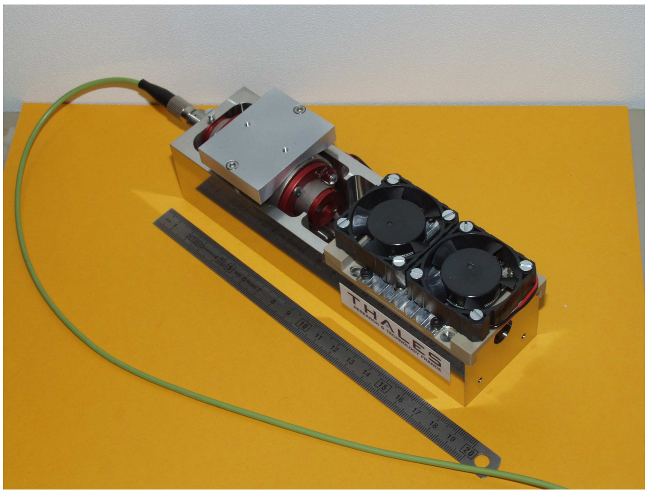
Another limitation was the short length of the delivery fiber and its multimode behavior that did not permit the remote pumping concept validation. As a consequence the pump laser had to be place nearby the OPO module and the fiber had to be fixed to avoid mode coupling. Her again, we believe there are solutions to fix this problem in the future. One of them is to use a lag e mode and strictly single-mode photonic crystal fiber for the delivery.

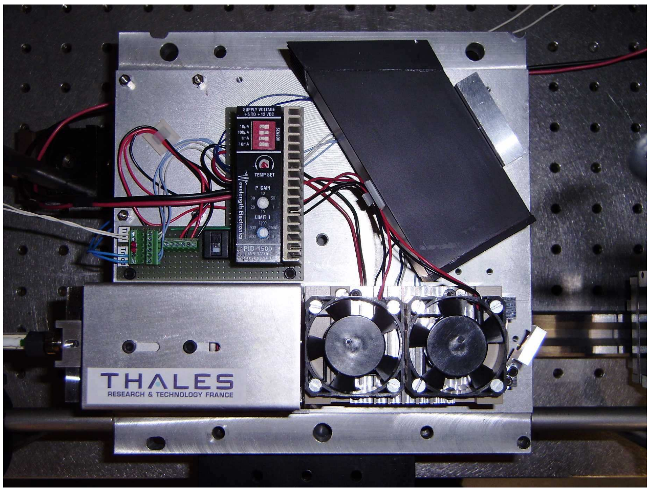
The figures below show respectively a CAD design of the fiber laser source and the prototype delivered to TRT for pumping the frequency conversion module.

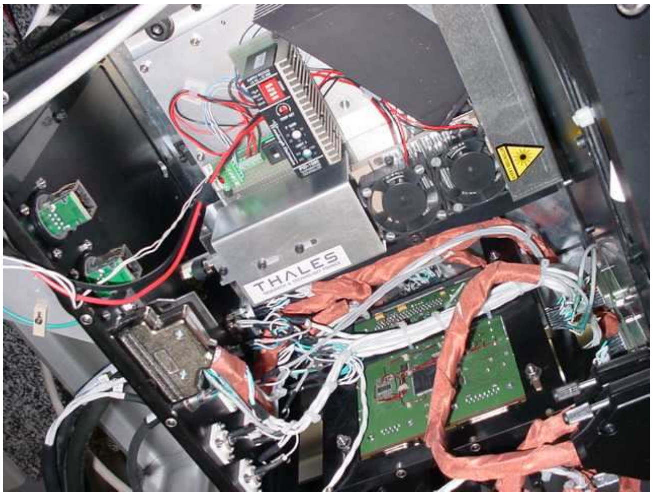




The OPO module integrated two nonlinear interactions into a single crystal and was fabricated without any moving part for maximum stability and reliability. It is also fiber coupled and connected with a standard FC connector. It has been operating consistently on a daily basis for more than a month before being delivered. Its integration within the turret was also successful and it proved to be reliable during the demonstrator validation tests. Although the conversion was presently limited due to the fiber laser broadened spectrum, we have shown previously that the optical to optical efficiency could be at least 25%. Overall, and including realistic 25 % wall-plug efficiency for the fiber laser, the goal of greater than 5% efficiency should be reached with this technology. The figures below show respectively the fiber coupled frequency conversion module on its own, the same placed on its base plate before its integration in the turret, and once inside the turret.







Please, refer also to § 4.4.4.4.

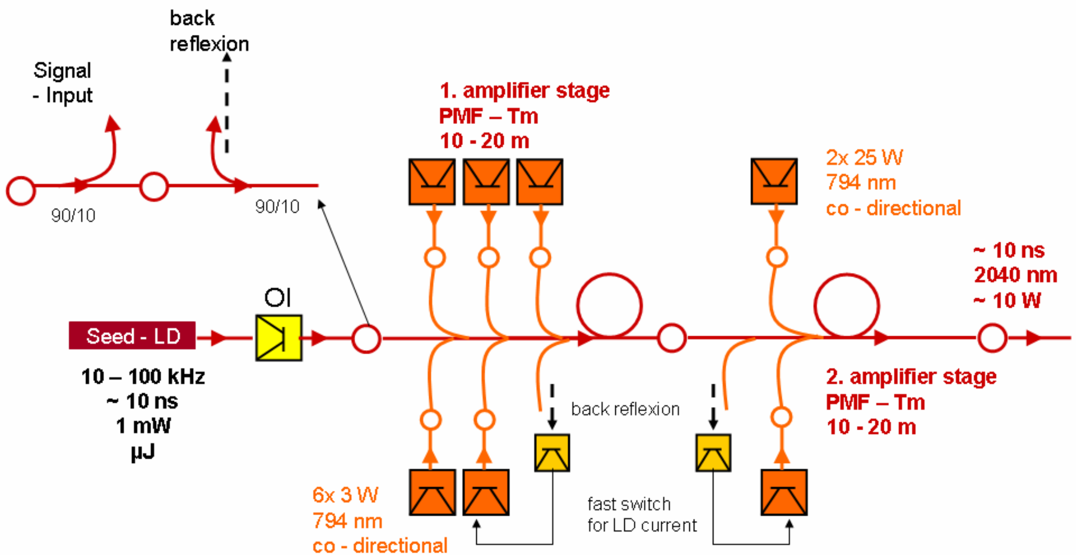
4.2.1.3.3. 2 µm fibre laser

The main goal of this task was to demonstrate a fiber laser system directly emitting in the 2 µm band, thus requiring only a single stage frequency conversion to add the 4 µm radiation. Furthermore, the 2 µm Tm-doped fibers can be directly pumped with 0.8µm GaAs based laser diodes with a potential wall-plug efficiency of around 20%. The approach taken was to study and build a monolithic fiber assembly consisting of a fiber oscillator and several amplifying stages connected with fiber splices and pigtailed components.

The progress was however slowed down due to the lack of fiber components developed for the 2 µm spectral range. This includes both Tm-doped active fibers and pigtailed components such as laser diodes for the seed, pump combiners, and high power isolators. In some cases, assembling mismatched fiber elements eventually yielded catastrophic damage of the diode laser pumps, preventing high power operation.

Despite these unsuccessful results, the fiber system has been fully designed and all the required components specified. It is expected that the missing parts will be soon available as 2 µm fiber lasers have recently raised a growing interest in the laser research community. As mentioned before, high power operation up to 30 W has been demonstrated in pulsed mode elsewhere using a spatial coupling laboratory set-up between amplifying stages. Moreover, the company Nufern recently disclosed a continuous wave laser prototype with 20% wall-plug efficiency. Although the oscillator/amplifier MOPA system that was foreseen in the project will require new components developments, we strongly believe that this approach is very promising for providing high average power at up to 20 % wall-plug efficiency.

The figure below shows the 2 µm MOPA design.



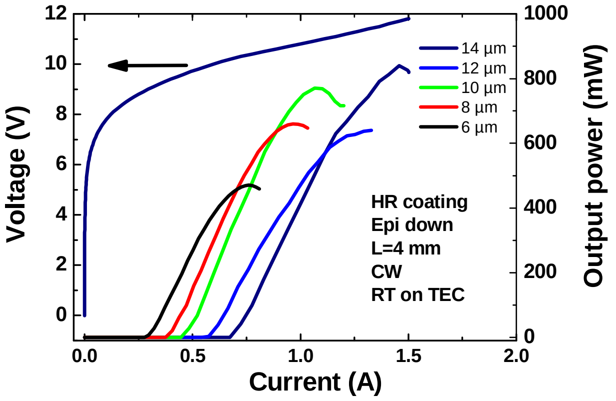
Please, refer also to § 4.4.4.5.

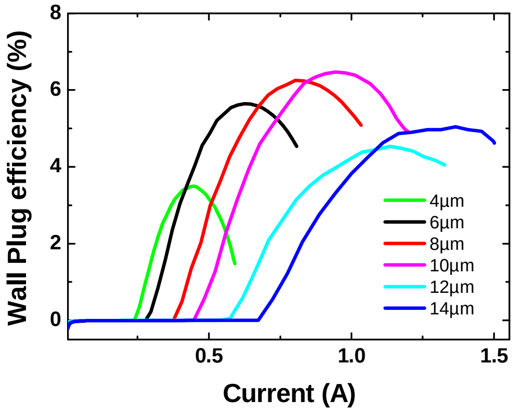
4.2.1.3.4. Quantum Cascade Laser

QCL are very attractive for the CASAM application with the prospect of being cheaper and more compact that the previous options with similar performances. The project focused on the 4 µm spectral range because the GaSb-based 2 µm laser diodes technology was already established.

The research effort spent during the project yielded very encouraging results, far above the targeted objective. Indeed, output powers of 250 mW at room temperature in CW mode at 4.6 µm, and 160 mW average power at 3.9 µm, have been demonstrated within the project initial time frame. Thanks to the project extension, up to 800 mW has now been demonstrated at 4.6 µm with near diffraction limited beam quality and up to 6% electrical to optical efficiency. These results have been reached thanks to a continuing progress in laser ridge design and processing technological steps. Moreover, it is now well established that, by adding a further buried technology step, output powers higher than 1W are achievable. These encouraging results undoubtedly keep the QCLs in the race to produce semiconductor lasers sources for the DIRCM application.

The figures below shows respectively a picture of a QCL chip as produced by ATL, the measured output power versus injection current, and the electro-optical efficiency versus injection current.





Please, refer also to § **Erreur ! Source du renvoi introuvable.**.

4.2.1.3.5. Future prospects

It is anticipated that with moderate further development the QCL technology could produce compact lasers emitting in the 4 to 5 µm range, with Watt–level CW or quasi-CW optical power, and around 10% wall-plug efficiency. This solution should probably be pushed if this power level proves to be sufficient for efficient jamming of missiles in a civilian aircraft threat scenario. It is also best suited with respect to footprint when only one spectral band is needed. However, as the number of required spectral bands is increased, the size and complexity of the source will also increase as it will be necessary to combine and align collimated beam issued form different semiconductor lasers.

This is not the case with the OPO technical option where all the beams are simultaneously produced along a common propagation axis. Also, the OPO technology has the capability of delivering higher average power as well as very high peak power for target range-finding and fine tracking, but obviously with a bigger size and at a higher cost.

4.2.1.4. IR image processing

The image processing is in charge of passive and active tracking.

The main tasks of the IR- processing that have been implemented are:

- Extraction and tracking of all objects within the field of view as well as the rating of the tracks.
- Determination of the target position in the image coordinates x and y.
- Sending target positions (real or extrapolated) in image coordinates to the turret in order to direct the passive and active systems to the target.
- Tracking on the simulator.

4.2.1.5. System processing

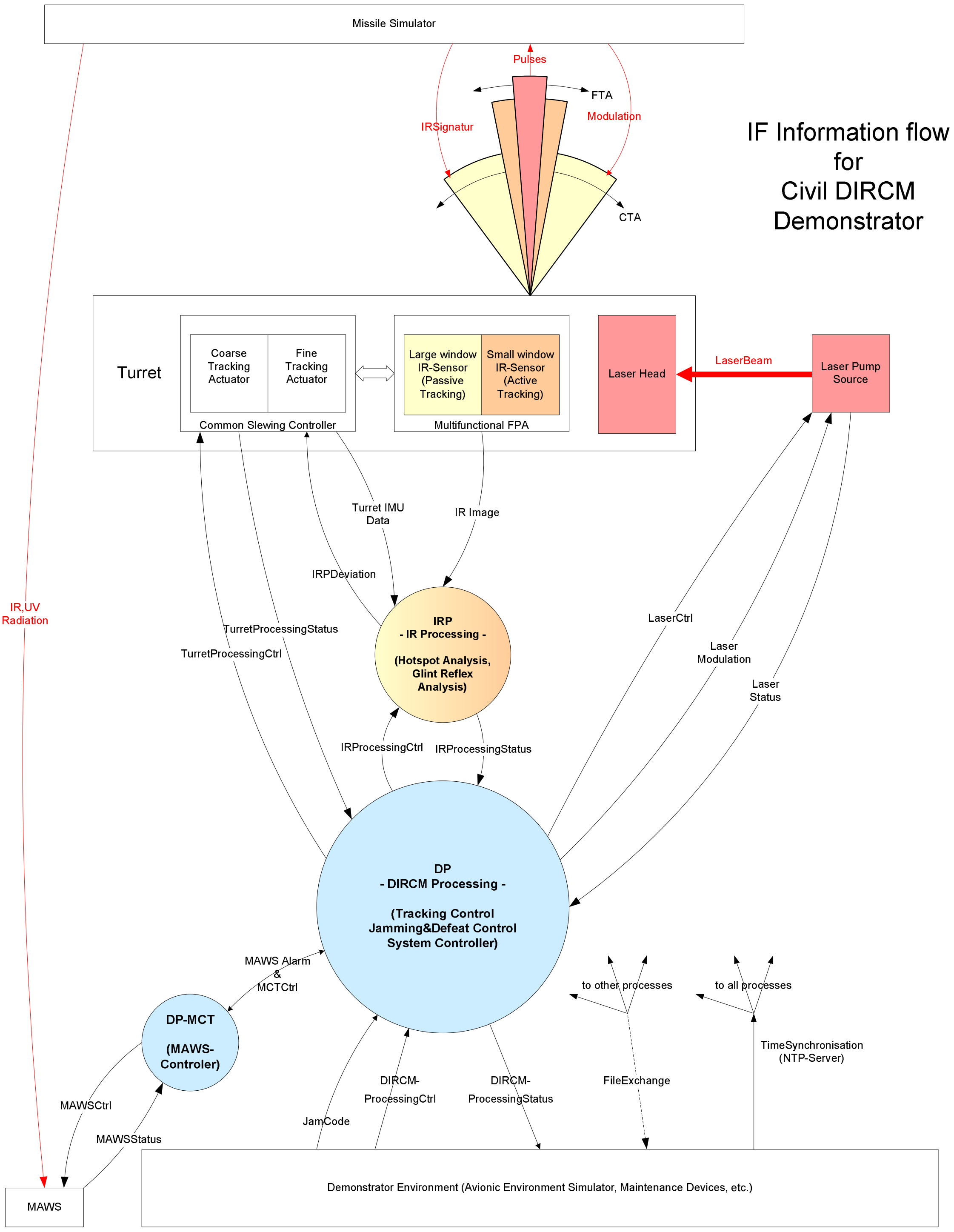
DIRCM Processing is divided into 3 parts, 2 main operational parts and one for test setup and recording purpose of the Demonstrator.

The IR Image Processing is supporting the closed loop tracking mode by analysing the IR Image and evaluating the target deviation in order to stay locked onto the target with or without laser beam, with or without modulated pulse train.

The DIRCM Processing could be seen as DIRCM controller. It has to handle each mentioned item (sub-device) in order to run in the correct sequence, in the correct timing and with the correct functions through the states of the command chain for defeating a missile.

The task of the Avionics Environmental System is to control and setup all the tests which are necessary for evaluation purpose of a DIRCM. All gathered information of the tests are recorded and stored within this device. The retrieved information can then be used for further analysis and evaluation.

In order to achieve a fast setup of the Demonstrator all non critical components were selected as standard off -the-shelf HW, equipped with standard ordinary multi purpose high speed interfaces such as Gigabit LAN where the message exchange is based on IP communication. The following diagram depicts once more the DIRCM Demonstrator architecture with an indication of the logical data flow.


IF Information flow
for
Civil DIRCM
Demonstrator
Missile Simulator
Pulses
FTA
Modulation
IRSignatur
CTA
Turret
Coarse Tracking Actuator
Fine Tracking Actuator
Common Slewing Controller
Large window IR-Sensor (Passive Tracking)
Small window IR-Sensor (Active Tracking)
Multifunctional FPA
Laser Head
LaserBeam
Laser Pump Source
Turret IMU Data
IR Image
IRPDeviation
IRP
- IR Processing -
(Hotspot Analysis, Glint Reflex Analysis)
TurretProcessingStatus
TurretProcessingCtrl
IR,UV
Radiation
LaserCtrl
Laser Modulation
Laser Status
IRProcessingCtrl
IRProcessingStatus
DP
- DIRCM Processing -
(Tracking Control
Jamming&Defeat Control
System Controller)
MAWS Alarm
&
MCTCtrl
DP-MCT
(MAWS-Controler)
MAWSCtrl
MAWSStatus
JamCode
DIRCM-ProcessingCtrl
DIRCM-ProcessingStatus
to other processes
FileExchange
to all processes
TimeSynchronisation (NTP-Server)
MAWS
Demonstrator Environment (Avionic Environment Simulator, Maintenance Devices, etc.)

The typical action sequence during a defeat cycle of the DIRCM Processing is:

1) waiting for an MAWS alarm,
2) pointing the turret towards the indicated MAWS angle,
3) triggering IRP to search for and track a hot spot,
4) switching Turret to tracking by hotspot,
5) enabling the Laser,
6) triggering IRP to search for and track a glint reflex,
7) switching Turret to tracking by glint reflex,
8) analysing the reflected modulation,
9) enabling jamming modulation of the Laser,
10) finally assessing the defeat success by means of the defined assumption.

4.2.2. Demonstrator tests outputs

4.2.2.1. Description of the test site and its environment

An outdoor test site for the investigation of optronic systems under realistic environmental conditions has been used.

It consists of a 400 m long ground path with a large 2-axis-motion simulator at one end with the capability of mounting test equipment. At the other end a sliding carriage is located for the setup of targets, which can move along a track with a length of 30 m in a perpendicular direction to the ground path. The fully closed off test site turned out to be attractive for cross-national investigations on experimental systems and demonstrator presentations

Top view

4.2.2.2. Description of the demonstrator installation on the testbed system

The CASAM demonstrator is shown in the figure below, already mounted on a large 2–axis-table, which was used as a hardware simulator for aircraft movements. The steering device on top of the black box as well as the provided MAWS on the lower right part of the DIRCM can be seen. The demonstrator position as seen below shows the standard test configuration. In the case of motion trials the table moved the demonstrator with sinusoidal profiles in azimuth and elevation around this point. The computers for turret processing, DIRCM processing, IR image processing, the avionics environment simulator, the motion control for the table and the sliding carriage control are all located in an adjacent room.

4.2.2.3. Description of one particular tests configuration with detailed information

With the above shown CASAM demonstrator testbed installation and a target setup as seen below the pre-defined trials were performed. A “missile” target was realised in the form of a lamp, emitting enough radiation to generate an alarm in the MAWS and sufficient heat to be used as IR source for the DIRCM imaging detector. The sledge could be moved laterally to the LOS of the DIRCM. The 2-axis-table and the sledge could be operated independently from each other from the laboratory. The laboratory served as operating centre for the trials, where the necessary computer devices were located.

For a typical trial the following steps were run:

- Set 2-axis-table to start position
- Set sledge to start position
- Check readiness of the motor
- Check readiness of IR processing

- Start DIRCM sensor display
- Select data to be acquired (DIRCM processing status, turret processing status, infrared imaging processing status, MAWS status, Laser status)
- Switch AES → Operational
- Start sledge motion
- Start table motion
- Switch AES → Standby
- Stop AES (closes data acquisition)

4.2.2.4. Key tests outputs

The CASAM DIRCM system has been validated by pre-defined ground tests representing an operational scenario. The trials can be divided into 4 groups:

- G1: Test without carrier and target motion
- G2: Test with target motion
- G3: Test with carrier motion
- G4: Test with carrier and target motion

For each test data from the different computers have been acquired (DIRCM processing status, turret processing status, infrared imaging processing status, MAWS status, Laser status). All these data were sampled and the most important were combined in one state diagram. The timeline between the different computers was set by a NTP service.

Generally the test results show that it was possible

- to manage the handover form the MAWS to the DIRCM
- to track the missile simulator passively in an autonomous way
- to direct a laser beam at the missile simulator
- to apply a jam code onto the seeker simulator

4.2.3. Synthesis of tests results

The whole combat sequence passing different states of the controlling DIRCM computer could be verified, starting from checking for a MAWS alarm, pointing the system LOS to the target, tracking the IR signature in passive mode and pointing the laser at the target.

Within the system integration phase at the test site in Röthenbach and during the trials execution the CASAM team could show the functionality of the DIRCM system and could gather a lot of information, although further parameter optimisation is necessary to come to a stable, reliable and fast system.

The reflected and modulated laser radiation was analysed using an FFT-algorithm. Based on the result of the calculation a subsequent switch to JAMMING could successfully be generated, sending a predefined modulation to the laser. This shows the closed loop jamming feature of the system. For operational closed loop jamming the selection of an adequate jam code based on the detected frequency spectrum of a seeker head is necessary.

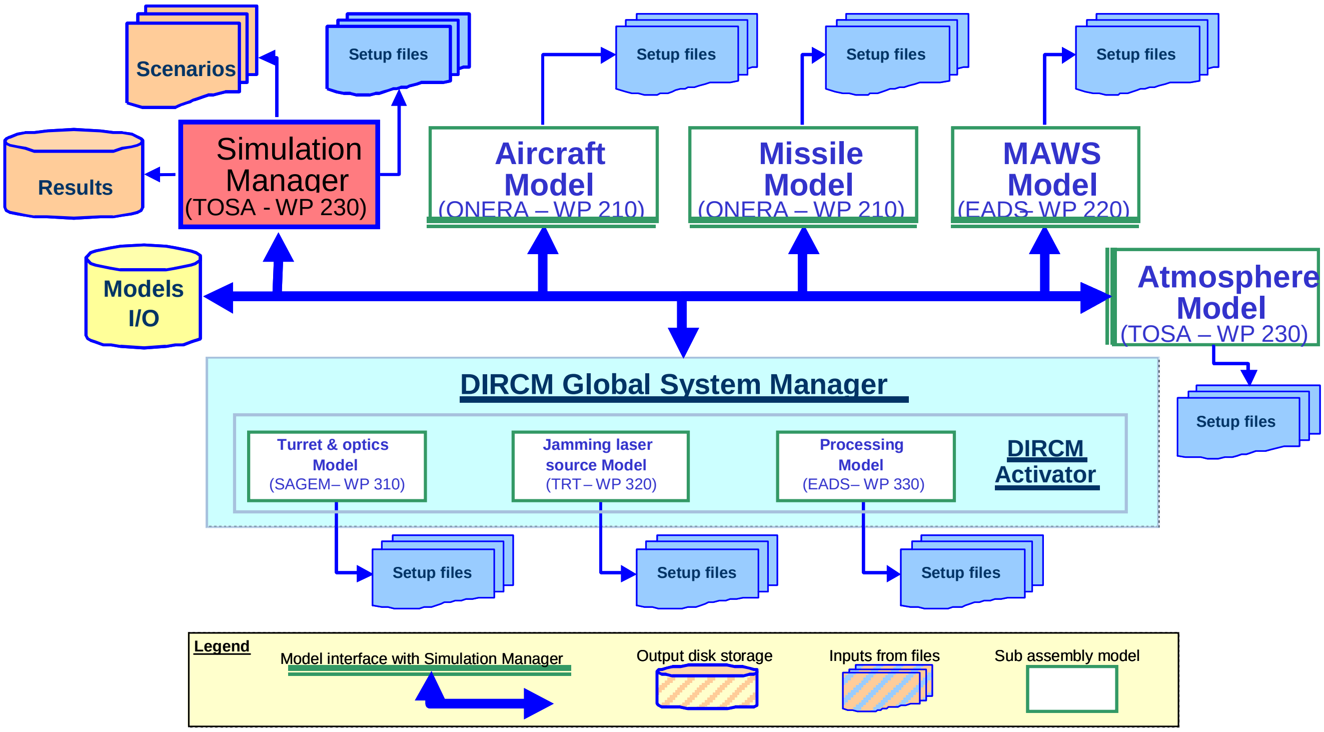
4.3. FLIGHT PROTECTION ACHIEVEMENTS

4.3.1. Simulation tools description

The simulation tools constitute a global system simulation, based on a discrete time loop, in which several modules and models are called sequentially according to the operation description of § 3.3 and 3.4, to reflect the actual DIRCM system operation during its mission : defeat incoming MANPADS missiles. The system is the DIRCM embedded on a civilian aircraft, facing the specific scenarios and actual threats as described in § 3.1 and 3.2.

The computer operating system is Linux. The simulation tools are developed in a MATLAB/SIMULINK environment, integrating C/C++/Fortran models of the sub-systems.

The simulation is not real-time based but is capable of massive computation in order to allow statistical studies and evaluation of mission success probabilities. Its architecture reflects the sequencing of the DIRCM operation in the global scenario environment, handling a complete set of simulation parameters:



The complete simulation software is structured into three distinct parts:

1) A software for scenario creation which allows easy definition of whole scenario information (parameters set), and which manages scenario data transfer to the calculation core through software calls or set-up files,

2) The calculation core, with all sub-assemblies models, which works with both configurations set-up files or direct software calls,

3) Some exploitation tools to analyse scenario intermediate and final results.

The Simulation manager software module, is used to generate scenarios (time management, handling of sub-models call sequence), launch batches for statistical study (Monte Carlo), manage input/output data (simulation input parameters, intermediate and final results, storage) and data exchange between sub models.

Each DIRCM sub-system is modelled by its input and output data, its behaviour and its performances. The models of the external sub-systems (aircraft, incoming missile(s), MAWS and atmosphere) are representative of their actual physical behaviour. The models are briefly described hereafter :

- The DIRCM model is split into three sub models : the Processing Activator, that handles the global behaviour of the DIRCM system and supervises the other DIRCM sub models through command sending and information transfers; the Turret and Optics Activator, that handles a lower and an upper performance turret type, and manages the turret slewing and the optical sensors (passive and active channels), as well as the laser activation; the Laser Activator, that manages the laser optical characteristics for two simultaneous wavelengths, and computes the laser emission.

- The aircraft model can handle A320, ATR72 and B747 aircrafts. It includes a kinematics model for take off and landing trajectory generation (dynamic computations) and an IR signature model computing the aircraft IR signature as a function of the missile line of sight, based on real IR signatures measured by ONERA. The model also handles a/c body optical obscuration for the A320.

- The missile model combines three interacting sub-models that can handle two types of missile: the seeker model, that computes missile lock state for launching and jamming state (classified values), the kinematics model, that processes launch command and lock information, and dynamically computes the missile trajectory, and the signature model, that computes the missile IR signature and laser cross section (classified values).

- The MAWS model provides the instant and direction of the missile detection (alarm declaration) along with the direction accuracy, and the indication of flight phase at declaration.

- The atmosphere model is based on reference propagation computation codes (MODTRAN/FASCOD) and simplified turbulence models; it handles transmittance, scintillation and speckle effects, and performs full spectral radiometric computations.

Intermediate (all data exchanged between models) and final results are stored into files. The final results file only contains the most important data needed to statistically analyze scenario results: the missile jamming status (deduced from the J/S evolution[1]), the defeat time and the defeat distance to aircraft (if missile declared jammed), the minimum missile-to-aircraft distance. The simulation ends if at least one of the following events occurs:

- The user-defined end simulation time is reached

- All the fired missiles are defeated (scenario success) and hit the ground

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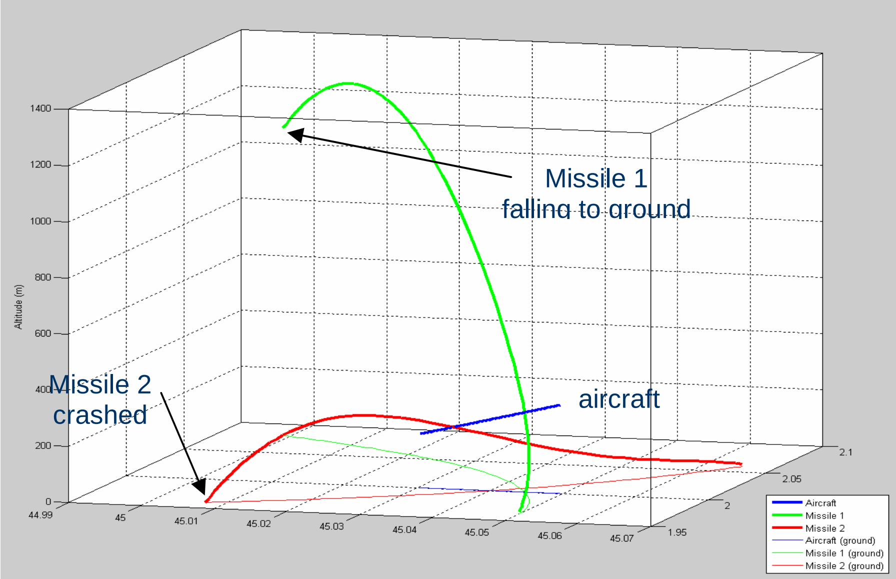
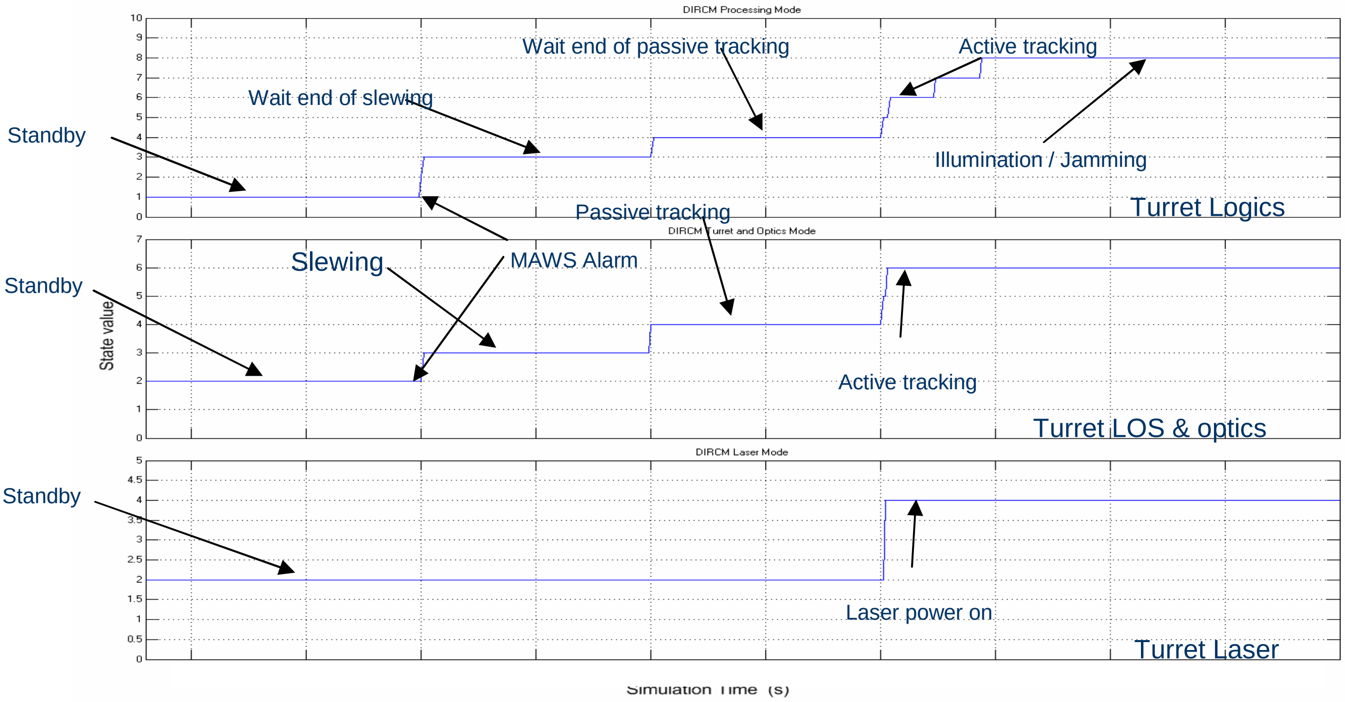
[1] The J/S is the ratio between the jamming laser energy and the collected energy emitted by the aircraft (infrared signature), which are both incoming into the missile seeker. If the J/S ratio is above a specified threshold during a predefined duration, the missile will be considered as jammed and will be declared as “killed”.

- One missile hits the aircraft (scenario failure : when the missile distance to the aircraft is lower than a user-defined threshold).

Exploitation tools allow 3D representation of the aircraft and missile(s) trajectories, and chronograms showing the internal state evolution of the DIRCM processing, turret and optics, and laser sub-systems :





The graph of missile-to-aircraft distances against time and the graph of the J/S ratio of each missile against time are also provided.

4.3.2. Validation tests

The actual validation of the simulation was made in two steps, corresponding to the 1st and 2nd steps of the simulation work.

- The 1st step was the validation of general architecture and functioning: pertinence of functional division, fullness of information exchange between the various modules, proper coupling with external software such as MODTRAN and FASCODE, coordinates systems and frame transformations, units of the various exchanged parameters…

- The 2nd step consisted in validating each module separately by directly using the simulation in specific configurations, for which the results can be simply calculated.

4.3.3. Expected achievable level of protection

The global DIRCM system simulation allows performance studies as a function of scenario, environment conditions and system design, and thereby assessment of success probabilities of the DIRCM mission in defeating incoming MANPADS missiles. A statistical study for mission success probability assessment has been performed in incremental steps so as to separate parameters and limit the huge combinatory possibilities.

The results of the statistical study have allowed assessing the expected level of protection against MANPADS as a function of atmospheric conditions, missile launch configurations, and DIRCM system design parameters.

As for atmospheric conditions, the J/S ratio is found to be always high enough with the nominal DIRCM and targets hypotheses taken. Passive tracking is always possible, but higher turbulence reduces the active tracking range which means that the jamming distance is mainly defined by the range of active tracking.

One weakness of the simulation is the conservative hypotheses for the seekers and the behaviour of the missile when it is jammed. To improve the simulation and our learning from the statistical study, real tests are necessary with real seekers. This was not possible in the context of the CASAM civilian program. The consequence is that the simulation might be pessimistic in some cases regarding the mission success.

An other main limitation of the simulation is the fact that the success of jamming is only represented by a J/S threshold and a J/S duration above threshold. This doesn’t take into account the adaptation of the jamming code to the seeker. Again, it was not possible to do else in CASAM without any test on real seekers. In a civilian program, it seems to be only possible to use generic codes. The simulation can also be pessimistic due to this reason.

With the hypotheses taken for the CASAM study, the results show that the CASAM DIRCM system is correctly defined and can protect the aircraft with a high mission success probability.

4.4. TRANSVERSE ACHIEVEMENTS

4.4.1. Legal achievements

Position in the USA:

- No legislation in force or pending, no subsidiary legislation (e.g. FAA regulations) requiring such systems.
- Unclear whether to expect legislation
- DHS programme: final (but limited) field testing of BAE candidate system and NG candidate system => final analysis including viability in commercial transport operations ?
- Central federal legislative framework
- Federal administrative framework with requisite expertise to set and enforce standards of performances

Position in the EU:

- No existing or pending legislation or subsidiary legislation (e.g. EASA civil aviation regulations or rules) mandating counter-MANPADS systems in commercial air transportation
- No developed federal legislative framework concerning security
- No EU body with requisite expertise to set and enforce standards of performances

Airworthiness certification of an optional counter-MANPADS system for use in commercial air transport can in principle be accommodated within the existing airworthiness regulations and codes (STC).

Airworthiness standards: uncertainties mainly relate to risk to third parties (on the ground or other aircraft in flight):

- Airworthiness standards will probably be in line with the operational standards.
- Need of a legislation giving certainty in respect of the safety standards to be applied

Conclusions:

Certification & Regulation: no major obstacle to obtain STC but it is desirable to have legislation giving certainty in respect of the safety standards to be applied (both for certification and liability regime purposes).

- EASA should be engaged in consultation to determine the standards in the near future and for the purposes of international consultation,
- To avoid inconsistencies between e.g the US and EU standards, there should be international engagement to harmonize standards: ICAO is a possible forum for such engagement, if not bilateral.

Transfer of Technology controls: uniform measures need to be addressed across the military and dual use technologies export control regimes of EU member States:

- Need of engagement on State to State level,
- Need of appropriate EU organ to engage with USA

4.4.2. Economics achievements

While the project is in its nature primarily technical with emphasis on innovation and development of countermeasure system against MANPADS, one should keep in mind that these devices are meant not only to protect national and global economies, but most of all human lives.

Nevertheless, this should be done within economically acceptable boundaries, meaning that cost of acquisition & operation of countermeasures on civil aircraft should not put an unacceptably high additional cost pressure on already troubled airline industry. On the other hand socio-economic effects of potential MANPADS terrorist attack on commercial airline in European Union should also be taken into account.

The purpose of the Economical Evaluation task was therefore to:

- ❑ support technical partners in understanding economic restrictions as regards to cost structures of airliners,
- ❑ cooperate in the definition of economically viable technical architecture of the countermeasure device – cost comparison of selected relevant technical solutions,
- ❑ support technical partners during the development process of selected architecture from the costing perspective of the target market – civil airliner’s industry,
- ❑ produce final financial cost estimates and cost breakdown structures for the selected DIRCM architecture,
- ❑ roughly estimate economic impacts of potential MANPADS terrorist attack on commercial airline in European Union,
- ❑ compare these costs to total financial costs of DIRCM (component & installation, training, operations, upgrades …).

We have started our work with the cost analysis of ‘comparable safety devices’ installed on civil aircrafts and with comparison of four different technological architectures of DIRCM considered during the first year of the CASAM project.

Selected ‘comparable devices’ – reinforced cockpit door with and without FDRAS (Flight Deck Remote Assistance System) and TCAS (Traffic-alert Collision Avoidance System) – are both used for safety purposes in civil aircrafts. While reinforced cockpit door is in principle relatively simple mechanical equipment, FDRAS and TCAS are more complex and predominantly electronic equipment. From a technical point of view, they should therefore be even more relevant when comparing their cost structures to DIRCM cost estimates.

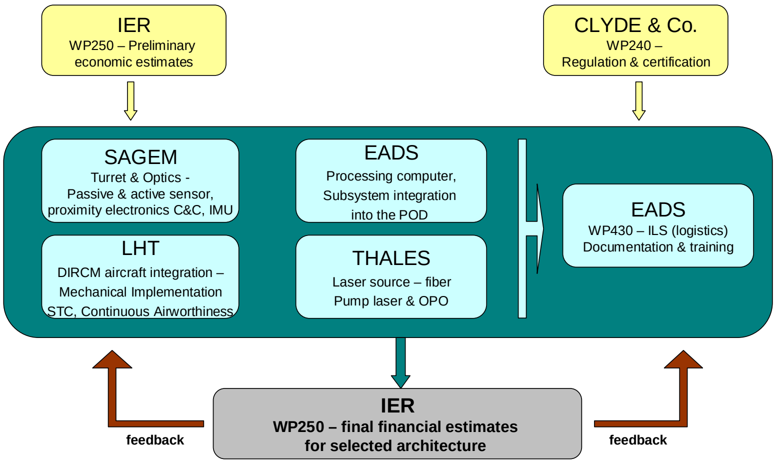
Besides getting some cost structure and cost magnitude insights for comparable safety devices used in civil aircrafts, it was even more important to use this exercise to develop the methodology for DIRCM cost analysis. Following this first phase and based on the definition of the four selected architectures, we continued our work to estimate costs for each of the four competing architectures that were considered relevant with the CASAM project.

Cost estimates for main components of the DIRCM architectures (including initial acquisition & installation cost as well as operational/maintenance costs) were roughly estimated by technical partners responsible for individual components or groups of them. Nevertheless, it is important to point out, that at that stage cost estimates were actually based on technical partners' experience with comparative components/devices. It is also important to point out that this economical estimates were 'rough estimates' based on very limited information – mostly because even technical issues have not been resolved completely, yet.

Since technical and even more financial differences between the four selected architectures were rather small (financial ranges of less than 3,5 € in case of 300 (6,2%) and less than 1 € in case of 3000 aircrafts to be fitted with DIRCM (2,2%)), technically superior architecture was chosen to provide civil aircrafts with the highest level of protection against MANPADS.

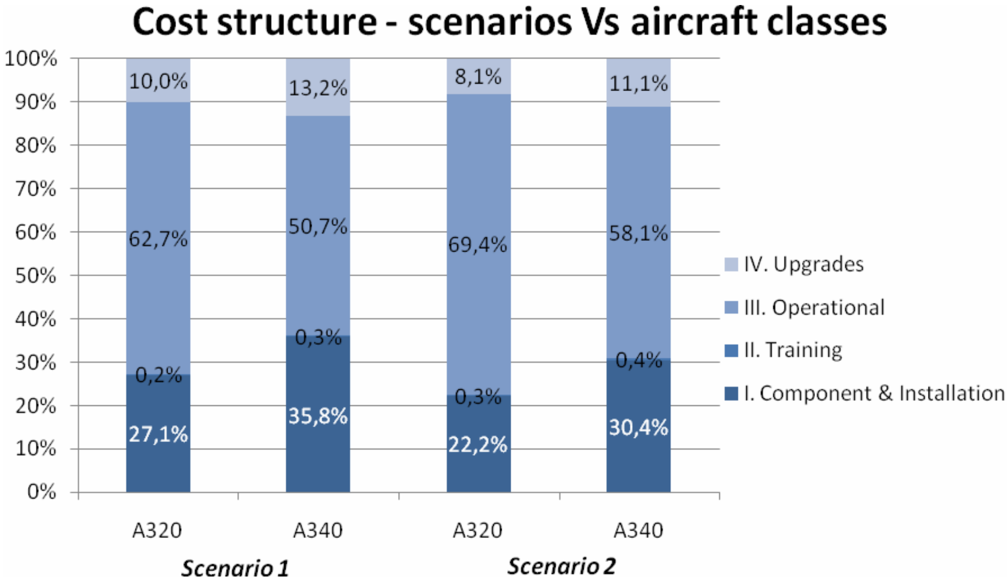
So, in the second phase we continued with the financial analysis of the selected DIRCM architecture. Cost figures have been gathered for each of the main DIRCM components including LRU system level, central power supply, control computer, laser pump, turret and MAWS. These figures were provided by contributing technical partners, based on iterative process that has started in the first phase already and using common-ground assumptions agreed upon by all contributing partners. Methodology has been developed and refined during the project duration and has provided all the partners with common understanding of financial issues regarding the DIRCM device developed within project.

COSTING INFORMATION FLOW



Total costs of DIRCM device per aircraft were estimated for two scenarios, each made up of a mix of two aircraft classes (A320 and A340). In scenario 1 (300 aircrafts to be equipped with DIRCM in 3 years) the total cost of DIRCM per aircraft (component & installation, training, operational, upgrades) was estimated at 7,8 million € for A320 (short flight cycle: 1,5 hour) and 5,9 million € for A340 (long flight cycle: 7 hour). In scenario 2 (3000 aircrafts to be equipped with DIRCM in 10 years) the total cost of DIRCM was estimated at 5,3 million € for A320 and 3,9 million € for A340 aircraft class.

In the following picture we can see that Component & Installation costs range from 22,2% to 35,8%, but by far the largest single category of costs are Operational costs. These range from 50,7% to 69,4% - in all cases they exceed one half of total costs estimated per aircraft. Upgrades represent from 8,1% to 13,2%, while Training costs are practically negligible ranging from 0,2% to 0,4%.



Finally, calculations of total DIRCM cost per flight cycle (FC) reveal it as a significant aircraft operating cost, adding some 220€ and 324€ per short range flights (A320, 1,5 hour; scenarios 1 and 2) to even 749€ to 1.142€ for long range flights (A340, 7 hour; scenarios 1 and 2). Recalculation of costs per flight cycle to cost per flight hour shows that short range flights in scenario 1 would be charged with additional 216€ and long range flights with 163€ per flight hour. In the scenario 2, short range flights would be charged with additional 147€ and long range flights with additional 107€ per flight hour.

From a passenger point of view the calculation of total DIRCM costs per ticket (per passenger per flight) seems very noteworthy information. We have estimated that DIRCM would add additional 1,8€ to 4,7€ of cost per ticket.

COST per TICKET (per passanger per flight)	Scenario 1: 300 aircrafts in 3 years		Scenario 2: 3000 aircrafts in 10 years	
	A320	A340	A320	A340
Average number of passengers 'on-board'	122	246	122	246
TOTAL	2,65 €	4,64 €	1,80 €	3,04 €

On the other hand economic impacts of potential MANPADS terrorist attack on commercial airline in European Union also needed some attention. We have started with literature dealing with economic consequences of different kinds of terrorist attacks around the world. Impacts are then divided into short-term (airline sector, financial markets impacts) and long-term (economic growth, foreign direct investment, trade, tourism).

From an ethical point of view human lives are priceless and this reason alone should be enough to do everything to protect human lives, including the use of DIRCM on civil aircrafts, if they can contribute to higher levels of safety. Nevertheless, we have used standard methodological approaches to estimate economic impacts of a potential ‘successful’ terrorist attack on a commercial airline in EU. We have estimated losses to as much as 139 to 238 billion EUR (taking into account indirect and induced effects) for the one-year period following the attack.

Fortunately, there is something we can do to minimize the probability of successful shut-down of a civil aircraft by using certain countermeasures. DIRCM device developed within CASAM project is certainly one way to do that. Therefore we have estimated also the costs of installing and operating DIRCM on different airplane clases within two scenarios that differ mainly in number of aircrafts equipped with DIRCM.

In the scenario 1 (300 aircrafts to be equipped with DIRCM in 3 years ; 50 A320 class aircrafts + 250 A340 class aircrafts) the total cost in 12 years life-time of the DIRCMs used on all 300 aircrafts would be approximately 1,857 million € and in scenario 2 (3.000 aircrafts to be equipped with DIRCM in 10 years ; 2.500 A320 class aircrafts + 500 A340 class aircrafts) the total cost would exceed 15,114 billion €.

COST STRUCTURES (12 year time-frame)	Scenario 1: 300 aircrafts in 3 years		Scenario 2: 3000 aircrafts in 10 years	
	A320	A340	A320	A340
DIRCM cost per aircraft	7.771.500 €	5.874.357 €	5.275.500 €	3.851.071 €
Number of aircrafts equipped with DIRCM	50	250	2.500	500
Total cost per aircrafts class	388.575.000 €	1.468.589.286 €	13.188.750.000 €	1.925.535.714 €
Total cost per scenario		1.857.164.286 €		15.114.285.714 €

1,9 and 15,1 billion € of total cost for installing and operating DIRCM on civil aircrafts seems very reasonable compared to 139 or even 238 billion € of potential losses caused by successful MANPADS terrorist attack.

It is also important to take into account the expected requirements of USA legislation demanding DIRCM-like countermeasures to be used on aircrafts flying to USA. European aircraft industry itself as well as European airliners could be put in an undesirable uncompetitive position, if this technology would have been not available to them or overpriced.

4.4.3. Installation of the full system on civil jetliners

4.4.3.1. Equipment location and aero-optics effects

The objective of this work was to propose suitable locations for the DIRCM equipment onboard a commercial aircraft, as it is fundamental that the DIRCM turret be able to emit its laser beam in any direction, without obstacle, below the aircraft, from –10° above the horizontal (negative elevation angle) to the vertical downwards, and that for 360° azimuth.

This study has proposed three concepts for aircraft integration and has given some elements for discussion, to evaluate them and identify the best turret location for best possible coverage. The main factors governing the integration are listed in a Comparison Matrix, which is a useful tool to rank the concepts. Initial scores rank the concept 3 (pod solution) as preferred solution, and concept 2 (in the pressurised area) as the least attractive.

The optical quality of the laser beam of a DIRCM system is influenced by two main factors:

- high-speed airflow in the boundary layer around the DIRCM turret : depending on the speed of the aircraft, the air optical density varies and leads to possible decrease in the optical quality of the beam;

- looking through the exhaust plume : due to this highly turbulent area, beam wander and beam spreading occur, and the intensity of the beam itself decreases.

The main objective of investigations on aero-optical effects was to study the negative influences of these effects. But it was soon found that during take-off and landing phases, as the speed of a plane is relatively slow as well as the resulting speed of the airflow along the fuselage, the effects of airflow on the system performance are very small. The work has thus focused on the second point, characterization of beam propagation in areas of very high turbulence generated by engine exhaust plumes.

The results observed with balloon burner experiments led to the conclusion that for passive IR-Imaging, critical regions could mean non transparent regions, which are defined by engine geometry and therefore plume boundaries, and that for laser beam pointing through these regions, the targeted precision of a DIRCM-System will be strongly affected.

The theoretical analysis has put in evidence some general features of turbulence effects : for instance turbulence scintillation effects are more severe for shorter wavelengths, while beam wander has no wavelength dependence, and in general, the final spatial resolution at sensor level is limited by turbulence rather than by diffraction-limited optics. Unfortunately a general statement about the applicability of lasers with different wavelengths is scarcely possible, as detailed calculations for varying wavelengths, beam diameters, and scenarios are necessary to make a decision which laser system would be most suitable for a specific task in the context of turbulence effects.

The experiments on the down-scaled jet engine have shown that the size of the plume as seen by the imager is highly dependent on the waveband used. For areas where the plume is transparent, very strong optical turbulence is degrading the imager as well as the laser performance: scintillation, blurring, beam wander, etc. are severe. The encountered frequencies are very high, which limits the use of adaptive optics unlike for tip-tilt correction. The experiments should be repeated with a jet engine (e.g. A320), including the selected spectral band of the DIRCM and a 2 μm and 4 μm laser.

Also to optimize the spectral band for the imager, spectral plume calculations should be performed. This has been done in a further work reported in D410.2.

The analysis shows, that the presence of plume leaves a substantial horizon area of the DIRCM sensors un-obscured. That means that the coverage field of DIRCM sensors, for both the proposed location of the pod and the integrated solution, is quite good as far as plume obscuration is concerned, with a slight advantage for the integrated solution.

Yet the data of plume size and shape as calculated by the version of NIRATAM Code used, did not take into account the plume’s axis deflection relative to the plane’s longitudinal axis. This deflection (angle between the plume’s and plane’s axes) appears during take-off and approach phases, as well as, side winds and banking of the aircraft. Due to this reason, the results of obscuration plots are considered to deviate from actual conditions.

Obscuration plots show the region, where a sensor’s field of view is blocked by its host platform and plume of the aircraft. This information is critical in selecting sensor location on the platform, as well as for masking the sensor’s field of view when doing image processing on DIRCM sensors data. Consequently obscuration plots can be exploited for evaluating the coverage capability of the DIRCM’s sensors for a determined sensors location on the aircraft as a function of sensors operation bands.

The Pros and Cons analysis has resulted in the confirmation of the pod solution choice as best compromise, although the integrated solution was found a little bit better in terms of obscuration, as the other key parameters are in favour of the pod solution.

4.4.3.2. Mechanical implementation

Once the equipment location on the aircraft has been studied and possible installation areas have been selected, mechanical issues have to be addressed. These issues concern the mechanical structure itself, its mechanical impact on the aircraft and the mechanical interface with the aircraft.

The purpose of WP420 was thus to study and propose solutions for mechanical implementation of the DIRCM System on a commercial aircraft, including a discussion on installation concept (podded or integrated solution) and possible changes in vibration characteristics due to DIRCM system installation, an analysis of the possible hindrances from already existing installations and of the cabling requirements, and a survey of certification requirements to be turned into requirements for system design.

The study has led to a complete design of the pod, including all related drawings, the structure consisting in an adapter plate, fittings for sensors and laser, angles to attach system components, bearings, two radome halves, a fairing and a seal. Sensors and laser special fittings have been carefully designed to guarantee unproblematic mounting and dismounting, accessibility to SRUs, wiring and other connections. The MAWS has also been carefully positioned inside the pod for optimal field of view.

The best location for installation on the aircraft has been identified and the design of the structural modifications for installation of the DIRCM system has been successfully carried out fulfilling all decided requirements

Regarding certification requirements, relevant regulation for the installation of the DIRCM system has been studied in detail and understood, so that possible means of compliance have been discussed. Moreover, the applicable airworthiness limitation items for A320 have been implemented in the design of the aircraft structure modification.

This very complete work gives a relatively precise idea of integrating such a system. It constitutes a solid basis for future work, that could be the study of the second option of integrating the DIRCM system LRUs inside the aircraft, the study of a better pod location by replacing an existing exterior installation, further verification of the design of structural modifications for strength using FEM analysis, or the study of other issues like ground handling and maintenance.

4.4.4. Technologies watch achievements

In order to support the project technical challenges (improvements in terms of size, volume, mass, reliability and efficiency), research activities have been conducted on some targeted technological topics : piezo-electric Ultra Sonic Motors, Multifunctional Focal Plane Arrays, use of composite materials, improved or new laser options for 2-color emission. These research activities have lead to actual development and application of innovative solutions in the CASAM demonstrator.

4.4.4.1. Piezo-electric motors

Progressive wave actuators are currently used in specific areas such as automobile sector, aeronautics, optics, house automation or robotics. These actuators are dedicated to low power applications up to 30W. In this operating domain, these actuators are offering the best torque to mass ratio. Their rotation speed and their rated torque allow direct use for many optronic applications. Travelling Wave Motors (TWM) are for instance commonly used in zoom focusing setups provided by the major’s camera manufacturers. In these applications, they are commonly called Ultra Sonic Motor (USM). Up to now, the commercially available motors are designed and manufactured by some Japanese Corporations.

In the CASAM project, the purpose of this technological study was to develop a specific high power USM suited to small-sized turret requirements for DIRCM applications, as well as a dedicated power supply allowing to apply all the newest control strategies developed for this type of technology.

The technological limitations (mainly the unavailability of commonly used continuous ring shaped ceramics for such high diameters) have been overcome thanks to the use of discrete ceramics (flex structure). In spite of performances lower than those which were aimed at, the motor with flex structure has appeared to represent a good technical compromise and the performances obtained are among the best ones for this type of motors. The final motor, mounted in the demonstrator, has a global behaviour very close to the well known behaviour of USR60 motor proposed by Shinseï Corporation, which is one of the leaders in Ultra Sonic motors (USM) design and production . It presents several advantages compared to other existing motors (high torque to mass ratio, high torque, break function).

The electronic control board developed for the demonstrator is a state of the art power supply, designed to improve motor and piloting performances, and decrease power supply size and weight. Its innovative definition allows to apply any of the new control strategies currently developed for this type of motor technology.

The piezo motorization developed for the CASAM demonstrator has proven the technical feasibility, but not the technological and industrial feasibility: the specified performances have been obtained but could not be maintained because of a lack of technology reliability.

Hence the estimated TRL at the end of CASAM is 2 for the ring motor technology; it is 4 for the motor control monitoring.

The effort to achieve a *feasibility study* for sufficient robustness is reckoned to be two additional years of development for a 20W motor. However a 20W motor might not be sufficient in fact in addition and today there is no other application identified for such power range.

4.4.4.2. Multifunctional Focal Plane Array

The Focal Plane Array (FPA) is the optical core of the DIRCM system and is one of the most important CASAM project technical challenges : in order to reduce the number of sensors and then to improve the system reliability, the FPA must be able to perform passive tracking, active tracking, and high speed identification of the missile. These functions are leading to highly demanding performances, not available on commercial infrared sensors. The goal of the technological research was to develop for CASAM a single high efficiency detector able to work in two bands and two modes (passive and active) with very low level of noise. Such an IR imager needs special features: windowing capability in order to improve frame rate, triggering capability, and “real time” switch capability between the video formats.

Based on the needs for DIRCM application, a research has been made to identify low ROIC sensors (appropriate to manage low optical signal levels), studies led by manufacturers on MFPA for laser-gated imaging and 3D imaging, and investigations on the time gating function, essential for temporal (ie spatial) filtering by opening an integration gate centred on the laser retro-reflected pulse (improved discrimination between active and passive signal). Specific experiments have been performed with a SAGEM InSb detector, to study the feasibility of the commutation between two video formats without losing video data and to evaluate the detector response to a short laser pulse for active tracking capability.

The tests performed have shown that the response of the InSb detector is fast enough to avoid to loose more than one image during commutation, which leads to the important conclusion that the FPA hardware is compatible with the new commutation function. The other result is that InSb FPA has a sufficiently broad bandwidth to detect the short laser pulses, and is fully compatible to fulfil the CASAM specifications.

From these research activities, a highly performing multi-functional FPA and the windowing have been defined, with the window full frame size chosen for best compromise between sensitivity and signal. The detector has been realized for integration in the demonstrator turret.

The study has shown that MFPA technology with bi-windowing is able to perform passive tracking, active tracking and identification without splitting the back reflected laser signal into separated channels. The interest is to simplify the optical design and to minimize the laser power.

In the frame of CASAM, the ability of the InSb FPA to switch from 100 Hz video (full image) to 4 kHz video (small windowing) has been demonstrated.

The estimated TRL achieved in CASAM is 5 and the main remaining work corresponds to a two-year industrialisation process for full qualified mass production MFPA in harsh environment.

4.4.4.3. Composite materials

Composite materials are widely used in automotive and aerospace industry in order to reduce weight, improve dynamical features, and reduce power consumption. The composite research topic was undertaken in the project in order to define optimized concepts & materials for the main moving parts, and to reduce turret inertia and weight.

A comparative study has been made between different composite materials used in airframe construction (fibre reinforced polymer matrix composites). These materials exhibit very interesting stiffness, tensile strength and density properties, which depend on the resin type used as polymer (thermoplastics and thermosetting materials), and on the reinforcing fibres used (aramid, carbon, glass fibres…). Epoxy resins are highlighted as out-performing most other resin types in terms of mechanical properties, resistance to environmental degradation and very good fatigue resistance. This leads to their almost exclusive use in aircraft components. The preferred reinforcing fibers are the carbon fibers.

The mostly used industrial processes for composite applications (resin transfer molding, filament winding, pultrusion…) have various advantages and market applications.

The knowledge from this research has been applied for the use in CASAM and the investigations have resulted in the recommendation of commercially available products as best option for the CASAM turret, and in the manufacturing of the demonstrator covers and optical base plate in the selected composite materials.

Advanced composite materials are already at TRL 9 and are already widely used in airframe construction. Their extended use in a future DIRCM product is highly recommended to improve performances ensuring at the same time high mechanical properties.

4.4.4.4. One micron fibre laser pumped frequency conversion module

The infrared laser source is a key component for the DIRCM system and its specificity is to emit several wavelengths in the 2 to 5 µm mid-infrared spectral range. The classical technological approach is to use mature diode-pumped 1µm solid-state lasers and frequency conversion stages (Optical Parametric Oscillators (OPO) modules) to provide the required spectral range. Two OPO modules are generally needed, which leads to complex optical arrangements and low overall efficiency of less than 2.5 %.

The goal of the technology research on this laser option was to improve the current state of the art with innovative solutions for compactness, efficiency and reliability, in the form of an actual laser source developed, packaged and delivered for integration into the CASAM demonstrator. Two improvements have been successfully realized compared to the classical DIRCM laser architecture:

- The bulk solid-state pump laser has been replaced by a fibre laser
- The two serial frequency conversion stages have been merged into a single one

As a result, a two-color mid-IR laser source consisting of a 1 µm polarized pulsed fibre laser pump and a single PPLN crystal OPO module was delivered to partners for the CASAM demonstrator. The 10 W polarized fiber laser emits 40 ns pulses at 40 kHz and is pumping an integrated two-stages frequency conversion module delivering Watt-level 2 µm and 4 µm radiation with balanced power. Furthermore, the pulse train can be modulated with the required bandwidth for DIRCM processing.

This laser source worked perfectly well after integration in the turret and after travelling to Germany, which proves the solid conception without any moveable parts. The obtained TRL according to CASAM demonstrator is 4, as no specific representative environmental tests have been made in the project.

Regarding the conversion stage, the CASAM OPO module has already shown to be a compact, reliable and efficient device, fabricated without any moving part for maximum stability and reliability. Overall, including a realistic 25 % wall-plug efficiency for the fibre laser, the goal of greater than 5% efficiency has been shown to be attainable with this technology without any particular additional research effort. This component can be considered as fully developed at lab level.

Regarding the 1µm fibre pump source, the CASAM laser source has proven to already reach almost all specifications and to be close to an actual fibre laser product. Based on CASAM achievements, the main remaining difficulties to overcome in this approach are

- ❑ the emission bandwidth broadening of the fibre laser, due to some remaining Four Wave Mixing effect, which limits the OPO efficiency and leads to some output power reduction,
- ❑ the multimode behaviour of the delivery fibre, which is detrimental to the OPO power stability and leads to a very limited fibre length, preventing from any remote pumping concept.

Solutions to solve these limitations already exist and can be developed in a near future :

- ❑ Emission bandwidth of the fibre laser : it is expected that one additional year of research and development will allow to suppress the remaining FWM effect and reach the full compliance with the specification.
- ❑ Limited length of the delivery fibre and multimode behaviour : the fibre needed here is very specific as it has to keep the light polarization state and withstand high peak power; with the standard fibre technology a trade off has to be made between the inner fibre diameter and non linear effects like mode coupling. There are solutions to turn around this problem in a near future. One of them is the use of a micro structured photonic fibre for the delivery as this technology permits the realization of strictly single-mode large mode area fibres (Crystal Fibre, Denmark, is already selling that kind of fibres). No further research is necessary, only the soldering between the delivery fibre and the laser active fibre has to be optimized.

4.4.4.5. Two micron fiber based pump laser

The main advantage of this new laser option is to require only a single stage frequency conversion to add the 4 µm radiation. The approach chosen in CASAM was to study and build a monolithic fibre assembly consisting of a fibre oscillator and several amplifying stages connected with fibre splices and pigtailed components (MOPA system).

Fibre preparation, fibre splicing and experimental setup for the laser wavelengths of 1.55 µm and 2 µm have been established, so that despite the unsuccessful high power operation, the 2 µm fibre system has been fully designed and all the required components have been specified as a result of the technology study. Design investigations have shown that the 2 µm Tm-doped fibers can be directly pumped with 0.8µm GaAs based laser diodes with a potential wall-plug efficiency of around 20%.

It has been demonstrated that an efficient complete monolithical 2 µm fiber amplifier system, with average powers of more than 10 W in pulsed or cw mode, can only be integrated and operated, if all fibre components with adapted fibre core and fibre cladding diameters are available for this spectral range, for lack of what destroying of pump laser diodes will occur, as well as heating and fusing of fibre splices.

As a matter of fact, the main difficulty in this laser option is the lack of fibre components developed for the 2 µm spectral range. This includes both Tm-doped active fibres and pigtailed components such as laser diodes for the seed, pump combiners, and high power isolators. As it has been experienced in the CASAM project in some cases, assembling mismatched fibre elements eventually yields catastrophic damage of the diode laser pumps, preventing high power operation. The TRL reached at the end of the CASAM project is estimated to be 2.

It is expected that the missing parts will be soon available as 2 µm fibre lasers have recently raised a growing interest in the laser research community (medical applications –however not requiring pulse operation-, DIRCM ..). High power operation up to 30 W has been demonstrated in pulsed mode using a spatial coupling laboratory set-up between amplifying stages (ISL, BAE Systems). The required high power withstanding fibres already exist. Moreover, the company NUFERN recently disclosed a continuous wave laser prototype with 20% wall-plug efficiency.

Based on CASAM investigations, laser specialists strongly believe that this approach is very promising for the providing of high average power at up to 20 % wall-plug efficiency and would be the best solution for a DIRCM system installed on civilian aircraft. There are no technological blocking issues, the still missing components (mainly a reliable isolator) would require one year of dedicated development.

4.4.5. User club achievements

The technical objective “User club dissemination” is fully dedicated to information dissemination with respect to the final product, the DIRCM; the project is working on through this first R&T step leading to a demonstrator to be dynamically ground tested.

Confidentiality rules around DIRCM activities (technical and commercial) did not allow a full completion of this WP.

Nevertheless, slides presented during the Final meeting on 25/06/2009 in Röthenbach have been distributed as “Publishable” documents and Consortium partners were encouraged to continue their own dissemination actions after the end of CASAM project.

Agora was the main communication tool between partners among the consortium and with EC and End User club.

Dissemination actions:

- NATO/ACG3/Sub-group #2 (SG2) during its spring meeting in Lisbon, PT, on June 6th, 2007 (20 mn presentation)
- First End User Workshop in Paris on 12/09/2007
- SPIE EUROPE Conference 17-20 September 2007 in Florence (Italy)

- Second and final End User Workshop in Röthenbach on 25/06/2009 with live trials on the demonstrator.

Appendix: Abreviations List

Abbreviations	**Full meaning**
A/C	Aircraft
CCM	Counter-Counter Measures
DIRCM	Directed Infra Red Countermeasure
DP	DIRCM Processing
FOV	Field of View
FPA	Focal Plane Array
HMI	Human Machine Interface
H/W	Hardware
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
I/F	Interface
IR	Infra Red
IRCM	Infra Red Countermeasure System
IRP	IR Processing
LCC	Life Cycle Cost
MANPADS	MAN Portable Air Defence
MAWS	Missile Approach Warning System
MWIR	Mid-Waveband Infra Red
MWS	Missile Warning System
NTP	Network Time Protocol
OEM	Original Equipment Manufacturer
ROIC	Read-Out Integrated Circuit
SARP	
SP	Sub-Project
S/W	Software
SWIR	Short Waveband IR
TCAS	Traffic-alert Collision Avoidance System
WBS	Work Breakdown Structure
WP	Work Package