Safe-Airport

Development of an Innovative Acoustic System for the Improvement of Co-operative Air Traffic Management

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D13 – Final Report with Journalistic Style Version

(Contract No.: IST-1-507008)

Document Number:	Security Classification:	WP:	Actions:	Issue:	Date:
03-130-RM-H16 Rev. 1	**PUBLIC**	**8**	**D13 Issue**	**1**	**19th September 2005**
				Issue: **2**	Date: **28th November 2005**

Total number of pages including this cover (excluding rear covers): **76**

Issued by: *D'Appolonia* ***[DAPP]***
University of Rome ***[UOR]***

Partners: *GRAS Sound and Vibration* ***[GRAS]***
Hytec Electronics ***[HYTEC]***
CRB Software Division ***[CRBSD]***
Aeroporti di Roma ***[ADR]***

Subject: *Publishable Final Activity Report*

W-Package: *8*

Deliverable: *D13- Final Report with Journalistic Style Version*

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ACRONYMS LIST

ATC	**Air Traffic Control;**
ATZ	**Aerodrome Traffic Zone;**
C2	**Command and Control;**
C2C	**Command and Control Computer;**
D	**Delivery;**
DandD	**Design and Development;**
EC	**European Commission;**
FAA	**Federal Aviation Administration;**
GUI	**Graphic User Interface;**
HD	**Hard Disk;**
HW	**HardWare;**
HWC	**Hard-Ware Component;**
HWCI	**Hard-Ware Configuration Item;**
ICD	**Interface Control Document;**
ISO	**International Organization Standard;**
IST	**Information Society Technologies;**
M	**Master;**
MFS	**Multi-Function Sensor;**
N.A.	**Not Available;**
NAS	**National Airspace System;**
OF	**Optical Fibre;**
RADAR	**RAdio Detection And Ranging;**
RX	**Receiver;**
S	**Slave;**
SMC	**Sensor Management Computer;**
SW	**SoftWare;**
WP	**Work Package.**

1 PROJECT EXECUTION

1.1 Introduction

The SAFE-AIRPORT project involved the development of an innovative acoustic system based on two Passive Phased Array Microphone antennas capable to discover and track airplanes up to at least six nautical miles distance in air and on ground. The system is completely integrable with airports air traffic management procedures and it is an effective air control system for ATZ (Aerodrome Traffic Zone), autonomous for smaller airports and integrated with standard control systems for greater airports. The system consists of two acoustic sensors, to be used in open environments, and a control unit linked to the sensor with optical fibers connection, with a control console, managed by an operator, to be installed inside the airport structure. Data survey portability to radar platform and data visualization and exchange are compatible with "Eurocontrol Standard Document for ATS ADEXP [DPS.ET1.ST09-std-01-01]". The main advantages of SAFE-AIRPORT system respect to radar systems will be the lower cost, the electromagnetic and acoustic pollution free. The system development included the complete simulation of the system, through the development of simulation software that includes outdoor acoustic environment modeling and the relative test scenarios. This allows to control system requirements and performances. The simulation was used both to guide system design and to verify system performances in collision-risk situations. The development of the simulation software was in compliance with "Federal Aviation Administration Standard Software Development for the NAS [FAA-STD-026]".

The two sensors (respectively called MASTER and SLAVE as shown in FIGURE 1) consist of plane 2-D phased arrays of microphones, a dome and control computer, which allows the sensor to perform the planning and the execution of the search and tracking activities in a prefixed search volume, in complete autonomy.

The sensors have a rotating antenna array plane and have a constant slope of 30° respect to the floor. The antenna plane contains a 2-D microphone array (512 microphones) forming an overall circular pattern.

The listening beam is electronically steered towards the selected search angular quantum (Search Task) or towards tracking direction.

The project was planned to be realized in two distinct steps (STEP 1 and STEP2). The first step of 18 months (financed by the present contract) included design and development of one sensor. An additional 3 month period was requested by the EC in order to carry out the field testing of the antenna prototype.

The second step (next 18 months not financed by the present contract) concerns the complementing of the first sensor and the production of the second sensor.

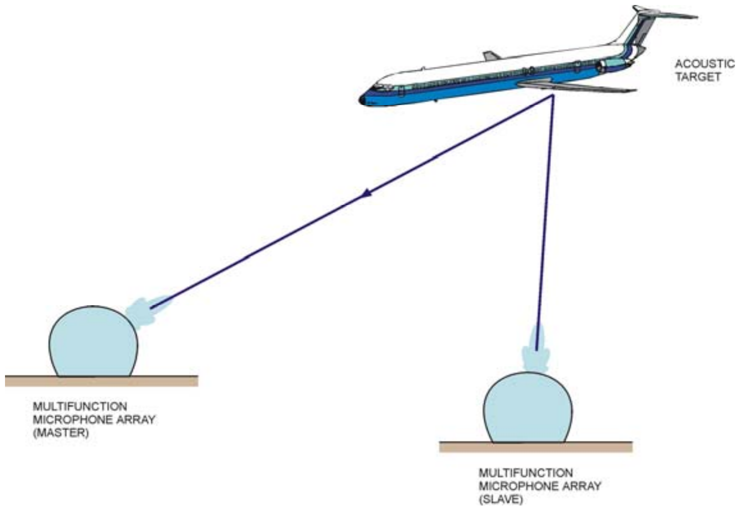

FIGURE 1 - SAFE-AIRPORT System - Employment Scheme

1.2 Project Objectives

Different objectives were meant to be reached in the first 12 months of the project and in a second period of 6 months, successively extended to 9 months. They were all achieved within established dates.

In the first 12 months of the project the following objectives were planned and achieved:

- full specification and design of the system and of the system simulation;
- full design and development of the project website, publication of the first scientific paper as contribution to an international conference of acoustics and Exploitation Plan writing .

The objectives planned and achieved in the last 9 months were as follows:

- full development of the Master MFS (Multi-Function Sensor) without rotation and dome;
- full development of the Command and Control Unit with associated GUI;
- full development of the software of the system simulation;
- exploitation action plan implementation and second contribution to an international conference of acoustics;
- field testing of the antenna prototype.

1.3 Contractors Involved

The project was coordinated by D'Appolonia S.p.A., an Italian engineering consulting firm. Other partners were:

- University of Rome "La Sapienza", Department of Technical Physics, an Italian research institute who was responsible for the simulation of the complete SAFE-AIRPORT system;
- G.R.A.S. Sound and Vibration AS, a Danish manufacturer of microphones, in charge of the realization of the acoustic sensors;
- Hytec Electronics Ltd., an English electronics firm who was responsible for the custom computers and DSPs;
- CRB Software Division S.r.l., an Italian software development company who was designing the graphical user interface of the system;
- Aeroporti Di Roma S.p.A. (ADR), an Italian airport management company who participated in the project as end user of the system.

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1.4 Work Performed

During the project, the work described in the following synoptic was performed with reference to the associated activity:

ACTIVITY	WORK PERFORMED
System and Testing Requirements Specification	Full specification of • System performance requirements • Acoustic targets • Testing requirements

ACTIVITY	WORK PERFORMED
	• hardware and software requirements
Simulation Software Design and Development	Full simulation software design Full simulation software development
System Software Design and Development	Full system software design Full system software development
Phased Array Design, Simulation and Development	Full phased array simulation Full phased array design Six months of phased array development Phased array laboratory testing Phased array field testing
Electronic Hardware Design and Development	Full hardware design Six months of custom electronic hardware development
Dissemination	Full project website design and development Contribution to the 148th Acoustical Society of America Conference in San Diego (US) Contribution to the 150th Acoustical Society of America Conference in Minneapolis (US)
Exploitation	Planning and execution of the exploitation
Project Management	Coordination of the project and of the three Contract Amendments

1.4.1 System and Testing Requirements Specification

The system and its internal interconnections were outlined. Moreover, a proposal is shown of the possible links between the system and the main airport entities while in operation.

The complete system is composed by the following components:

- Master MFS (Multi-Function Sensor);
- Slave MFS;
- Command and Control Computer (C2C).

Each MFS rotates at a speed of 4 seconds per turn and sees the instantaneous hemisphere divided in 2500 Angular Quanta. The frequency Band of the measurements reaches the 10 KHz corresponding to a minimum sampling rate of 20 Ksamples/sec (according to the Nyquist theorem). Each measurement comprises 64 samples equally spaced in the frequency band. The MFS is based on an antenna array made of 512 equally spaced microphones. The antenna array has a diameter of about 2 meters.

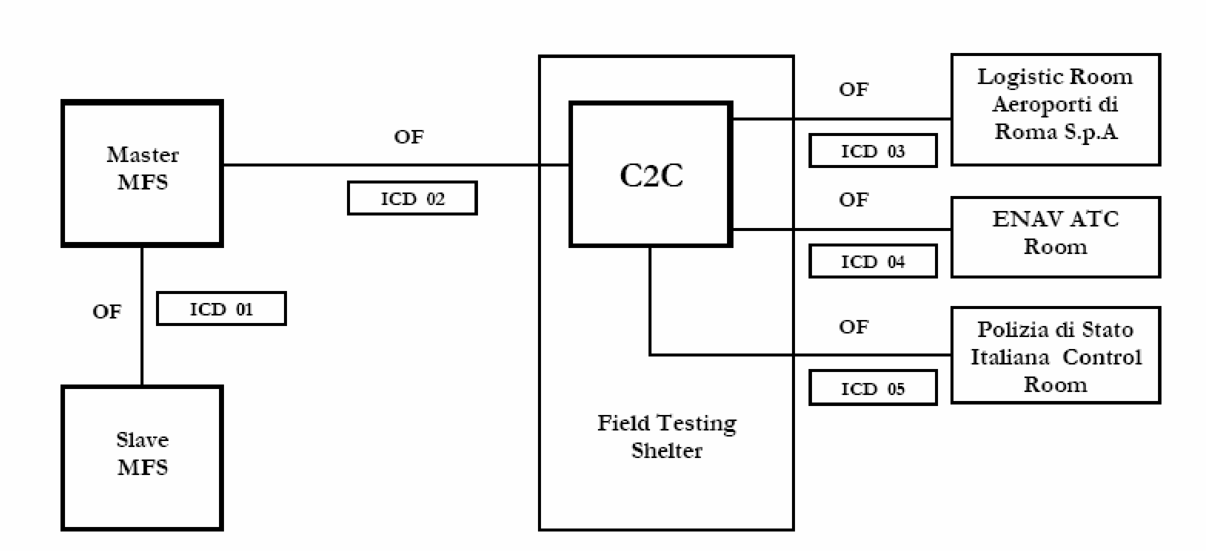


FIGURE 2 - SAFE-AIRPORT system data exchange layout.

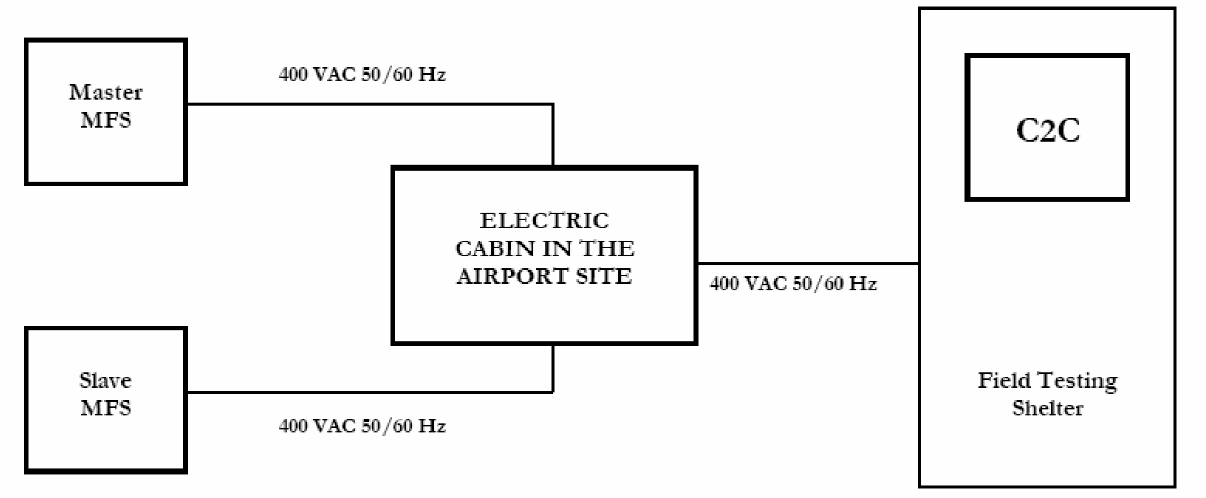


FIGURE 3 - SAFE-AIRPORT system power supply layout.

ITEM HIERARCHY	*DESCRIPTION*
SAFE-AIRPORT	SAFE-AIRPORT System
- Master MFS	Master Multi Function Sensor
- Slave MFS	Slave Multi Function Sensor
- C2C	Command & Control Computer
TOTAL	*4*

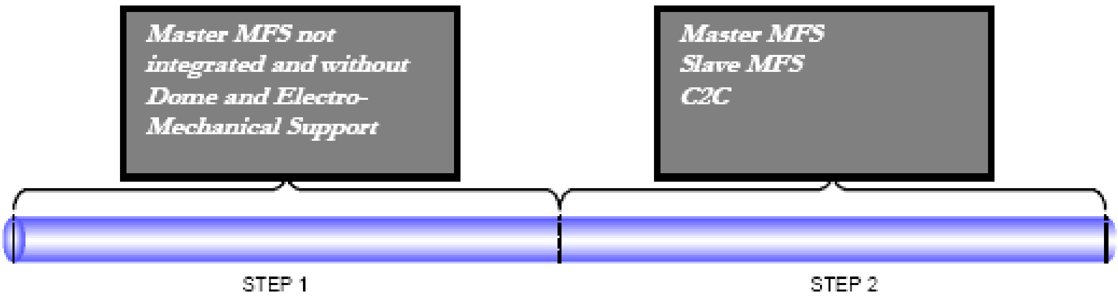


FIGURE 4 - SAFE-AIRPORT Subsystems and STEP1-STEP2 Subdivision.

The desired general system and performances requirements for the SAFE-AIRPORT system are indicated in the following synoptic:

SAFE-AIRPORT System Performances	
PERFORMANCE	*DESCRIPTION*
Number of Sensor **[REQ_SYS_02]**	Two Phased Array Antenna (Master Sensor & Slave Sensor)
Rotation Speed **[REQ_SYS_03]**	90°/sec
Azimuth **[REQ_SYS_04]**	0° ÷ 360°
Elevation **[REQ_SYS_05]**	0.7°÷90°
Range Max **[REQ_SYS_06]**	6 Nautic Miles
Number of Angular Quantum Crowns **[REQ_SYS_07]**	45 (44 VOS + 1 HOS)
Angular Quantum Number **[REQ_SYS_08]**	2500
Search Data Rate (2D Search) **[REQ_SYS_09]**	8 sec
Tracking Data Rate (3D Tracking) **[REQ_SYS_10]**	4 sec
Wideness of the Narrow Beam **[REQ_SYS_11]**	2.6° (at 3 dB)
Wideness of the Wide Beam **[REQ_SYS_12]**	6° (at 3 dB)
Maximum number of measures **[REQ_SYS_13]**	312.5/sec (64 samples/measure)
Frequency Band **[REQ_SYS_14]**	(0÷10 KHz)

STEP 2

Testing sites and scenarios were also defined. The sites available to locate the antenna for field testing were defined in the Fiumicino-Rome Airport taking into account the present airport regulations.

In fact, all the installation site and installation procedures were chosen in compliance with national and international law for airports management. In particular, in Italy, ADR must take into account the following regulations:

- ICAO: Annex 14, 1999 Edition;
- ICAO Doc. 8168;
- ENAC: "Regolamento per la costruzione e l'esercizio degli aeroporti" 2nd edition, 21st October, 2003;
- AIP ITALIA (Aeronautical Information Publication, Italy);
- Italian Law 4th February 1963, N° 58;
- Navigation Code.

Among the possible sites, UOR decided the most suitable one for the trials, depending on aircraft trajectories.

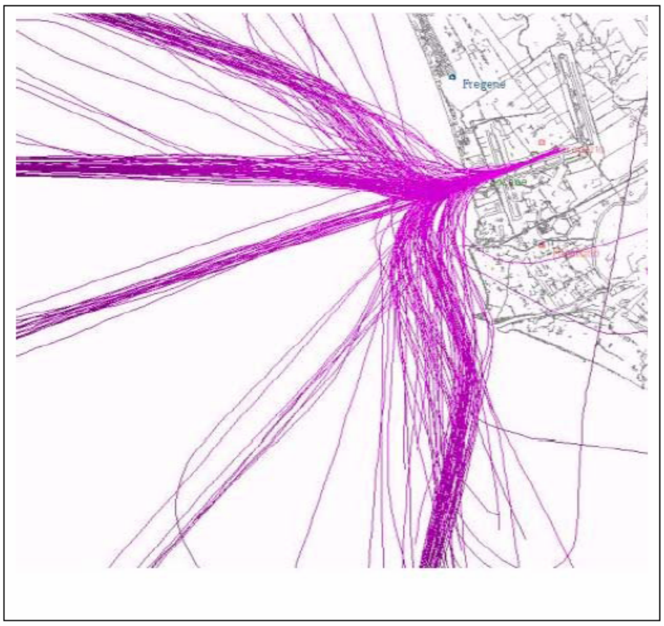


FIGURE 5 - Recorded Radar Tracks Implied by Take-Off Flights in Fiumicino ATZ.

A choice was made also regarding the best aircraft models to be used in test trials of the system. On the basis of typical traffic in Fiumicino-Rome Airport, the McDonnell Douglas MD-80 was selected as a reference model.

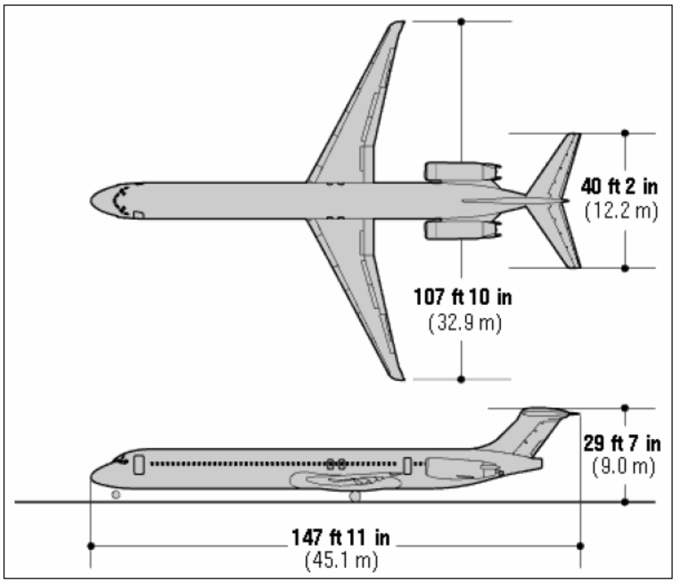


FIGURE 6 - MD80 Mechanical Layout

The most common standard scenarios (take-off and landing) were carefully described with the support of trajectories drawings and with reference to the Fiumicino-Rome Airport. Moreover, some possible risk scenarios involving collisions were considered.

A tuning of the site choice for field trials was performed among those pre-selected, based on the available drawings and on technical consideration like the range of the system and the best coverage of the Aerodrome Traffic Zone around the airport.

The spectral characteristics of the acoustic emissions of the involved aircrafts were also investigated with the help of professional literature search and some data processing. This investigation served as guideline to the design of the antenna array of each MFS.

After that, some simulations showed the beam-forming efficiency of various antenna arrays with different number of microphones. By beam-forming, it is intended the capability of the antenna array to focus very narrowly its total beam by opportunely shifting and summing the output of its multitude of microphones.

The mutual distance between each couple of microphones defines the maximum working frequency of the beam-forming antenna array while the size of the array determines the width of the focused beam and hence, the resolution of the beam-forming. It appeared clearly from simulations and diagrams that at least 500 microphones are needed in order to obtain a beam as narrow as wanted.

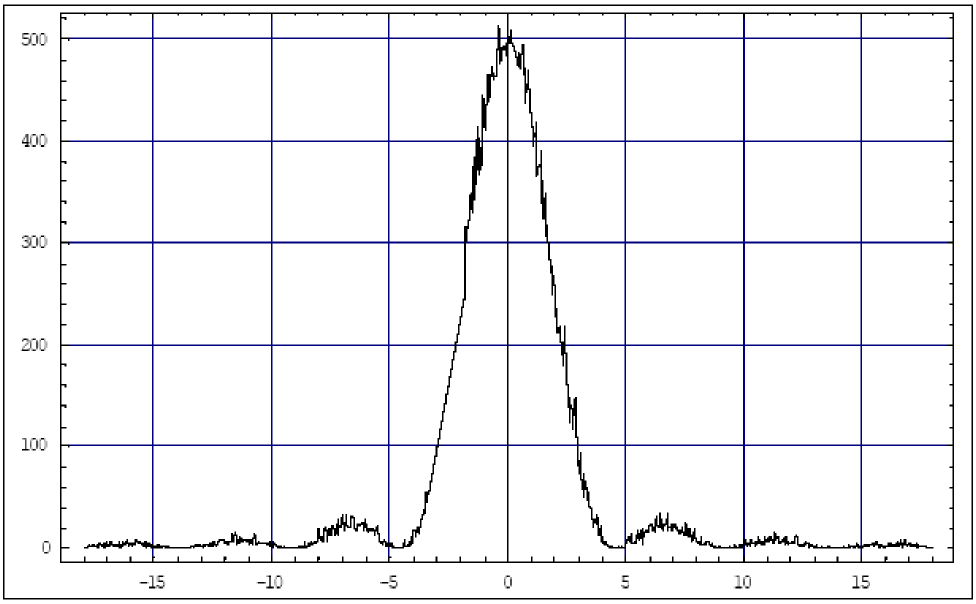


FIGURE 7 - Directional Sensitivity of a Simulated Circular Array Affected by Amplitude and Phase Noise.

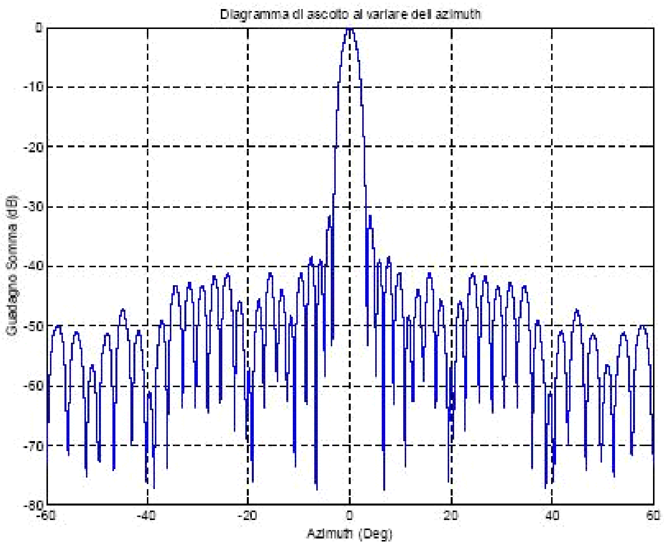


FIGURE 8 - Listening Beam (Azimuth Cut).

The hardware requirements of sensors, computers and their main components were described in detail. Most importantly, the study was focused on the following configuration items of each MFS:

- antenna;
- hardware and electronics.

As regarding the computer, the main configuration items considered were:

- storage;
- network;
- man-machine interface;
- CPU;
- computer wiring.

The objectives achieved about system and testing requirements specification were:

- detailed description of components structure and of the interconnections between both hardware and software components;
- description of the performance of the system and of individual main components by requirements coding;
- detailed description with the support of technical drawings of the installation sites of the Master MFS and Slave MFS; description of a reference landing scenario and a reference take off scenario;
- detailed description of two risk scenarios concerning the possible collision between two aircrafts;
- definition for the field testing activity of the optimal installation site with reference to the possible sites determined at the level of testing site definition;
- acoustic spectra of the involved aircrafts and preliminary assessment of the beam-forming performance;
- outline of the beam-forming fundamental theory;
- detailed description of the mechanics and aerodynamic features of the aircrafts involved in the scenarios;
- preparation of a matrix of system requirements vs. verification methods (analysis, demonstration, inspection, test);
- detailed description of the hardware requirements of the Master MFS, the Slave MFS, the Command and Control Computer (C2C) and their main components;

- detailed description of the software requirements of the Master MFS, the Slave MFS, the Command and Control Computer (C2C), the simulation software and their main components;
- development of the following document drafts: "Acoustic Tracking System Requirements for ATZ Control Applications", "Acoustic Track Data Format for ATZ Control Applications", "Acoustic Monitoring System Requirements for the ATZ Acoustic Levels Prediction" and "Acoustic Monitoring System Database Management for the ATZ Acoustic Levels Prediction";
- description of the guidelines to develop software in agreement with the FAA-STD-026A standard applied to the single software item;
- preparation of a matrix with the system requirements and components vs. the criticalities of the project with possible recovery actions;
- preparation of a matrix of system requirements;
- preparation of a matrix of system requirements for each responsible partner.

The following synoptic shows the achievements made:

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
Description of the performance of the system and of individual main components by requirements coding.	Performance requirements of the hardware items quoted above; Performance requirements of the software items quoted above. ***[All]***
Detailed description of components structure and of the interconnections between both hardware and software components.	Interconnection scheme between the following hardware items: antenna, sensor management computer hardware, data acquisition hardware, wiring, command and control computer; Interfacing scheme between the following software items: signal processor, data handling, sensor control; Interaction scheme between hardware and software items. ***[All]***
Outline of the beam-forming fundamental theory.	This theory was provided and served as guideline for the phased array simulation and design ***[UOR]***
Detailed description with the support of technical drawings of the installation sites of the Master MFS and Slave MFS; description of a reference landing scenario and a reference take off scenario; detailed description of two risk scenarios concerning the possible collision between two aircrafts.	Definition of several sites, shown in proper drawings, within the Rome-Fiumicino Airport, where the Master and Slave antennas could be installed in agreement with technical requirements and actual airport regulations. ***[All]***
Definition for the field testing activity of the optimal installation site with reference to the possible sites	Tuning the site choice by defining the optimal site, among those pre-selected, for the installation of the

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
determined at the level of testing site definition; acoustic spectra of the involved aircrafts and preliminary assessment of the beam-forming performance.	antenna for the field testing activity; Definition, through literature search and data processing, of the spectra of the involved aircrafts ***[DAPP][UOR][ADR]***
Detailed description of the mechanics and aerodynamic features of the aircrafts involved in the scenarios.	This information was provided and helped the acoustic target specification ***[DAPP][UOR][ADR]***
Preparation of a matrix of system requirements vs. verification methods (analysis, demonstration, inspection, test).	This matrix was provided and helped the design and development phase ***[DAPP][GRAS][HYTEC]***
Detailed description of the hardware requirements of the Master MFS, the Slave MFS, the Command and Control Computer (C2C) and their main components.	Detailed description of the hardware items and their components ***[DAPP][GRAS][HYTEC]***
Detailed description of the software requirements of the Master MFS, the slave MFS, the Command and Control Computer (C2C), the simulation software and their main components.	Detailed description of the software items and their components ***[DAPP][UOR][CRBSD]*** ***[ADR]***
Development of the following document drafts: "Acoustic Tracking System Requirements for ATZ Control Applications", "Acoustic Track Data Format for ATZ Control Applications", "Acoustic Monitoring System Requirements for the ATZ Acoustic Levels Prediction" and "Acoustic Monitoring System Database Management for the ATZ Acoustic Levels Prediction".	These norms were outlined and are an added value of the project ***[DAPP][ADR]***
Description of the guidelines to develop software in agreement with the FAA-STD-026A standard applied to the single software item.	These guidelines were followed during software development ***[DAPP][UOR][CRBSD]***
Preparation of a matrix with the system requirements and components vs. the criticalities of the project with possible recovery actions.	Achieved as planned ***[All]***
Preparation of a matrix of system requirements	Achieved as planned ***[All]***
Preparation of a matrix of all hardware and software items for each responsible partner.	Achieved as planned ***[All]***

1.4.2 Simulation Software Design and Development

The partner responsible for the design and the development of simulation software was the University of Rome "La Sapienza" (UOR).

The simulation software is based on a modeling of the acoustic environment, acoustic sources and system algorithms with a temporal quantization of the events with a time step of 10 ms. In other words, the simulation was built up with a temporal granularity of 10 ms for simulation scenarios (aircraft trajectories) lasting a few minutes. Every run of the simulation is starting from peculiar conditions defined stochastically according to the Montecarlo method. Every test run can be repeated because the random seeds are saved on output files.

The module MFS concerns with the modeling of the Multi-Function Sensor corresponding to the rotating phased array of microphones together with the antenna computer.

The scenario module is about the acoustic dynamic representation of the simulated aircraft trajectories.

The Command and Control module deals with the representation of the command and control algorithms necessary to the management of the database of the confirmed aircraft tracks and to the communication of aircraft detection to external networks.

In the general initialization, the locations of the antenna microphones and the aircraft trajectories are loaded. The run initialization implies the initialization according to a stochastic parameter of the starting rotating position of the antenna and a first rotation (without targets) to initialize the algorithm of exploration of the angular search quanta.

The function of search of the acoustic sources is based on the discretisation of the hemisphere in 2500 angular quanta laying on circular crowns and geometrically corresponding to the circular opening of the listening beam. The quanta are cyclically reused (data rate of 8 seconds) to perform search measurements for acoustic sources in the hemisphere.

The objectives reached are as follows:

- software architectural design of the full assembly of the simulation and its individual components;
- technical recommendations concerning integration of the software;
- graphic representation of the structure of the software tree;
- description of the interfaces between the various software components;
- software development of substantial parts of the simulation and its individual components.

The following synoptic shows the achievements made.

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
Software architectural design of the full assembly of the simulation and its individual components.	Design of the simulation software and all its modules ***[UOR][ADR]***
Technical recommendations concerning integration of the software.	Achieved as planned ***[UOR]***
Graphic representation of the structure of the tree of the calls for every software item.	Achieved as planned ***[UOR]***
Description of the interfaces between the various software items.	Achieved as planned ***[UOR]***

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
Software development of substantial parts of the Simulation and its individual components.	Software development of the configuration software computer item of the simulation software; ***[UOR][ADR]***

1.4.3 System Software Design and Development

Software to be used for the implementation of the final system was designed and developed under the responsibility of D'Appolonia SpA.

The Master MFS sensor management software is composed by the following items:

- signal processor;
- data handling;
- sensor control.

The Master MFS software development was in compliance with international standard FAASTD- 026A (USDT, 2001).

The Command and Control Computer (C2C) software receives the track data from the sensor and shows the radar map Elevation-Azimuth on the first monitor. The second monitor shows a list of track situations, organized in tables on multiple windows, adopting a threatening classification in terms of accident potential risk. The operator has the possibility to zoom locally to improve the resolution of radar map details. The C2C software data involved in the process is stored into a relational data base management system.

The C2C software sends the risk situation data towards security bodies and track data towards radar system management bodies. Risk situation data are used by security bodies as an alarm signal and start a verification process as a communication of a verification request to ATZ control bodies. They can use track data towards radar systems as a potential external appointment.

Risk situations regard collisions between flying aircraft, between landing aircraft and aircraft standing on ground, between landing aircraft and ground vehicle and between ground vehicles are analyzed by the C2C software.

The Command and Control Computer software is composed by the following items:

- Command and Control;
- Graphic User Interface (GUI).

The C2C software was developed in compliance with the international standard FAA-STD-026A (USDT, 2001) and with the Eurocontrol Standard Document for ATS ADEXP [DPS.ET1.ST09-std-01-01].

The objectives regarding this issue were the following:

- software architectural design of the full assembly of the Master MFS and its individual components;
- software architectural design of the full assembly of the Command and Control Computer and its individual components;
- technical recommendations concerning integration of the software;
- software development of substantial parts of the system software and its individual components;
- completion of the software development of the system software and its individual components with associated GUI.

The following synoptic shows the achievements made:

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
Software architectural design of the full assembly of the Master MFS and its individual components.	Design of the system software of the Master MFS (signal processor, data handling, sensor control) and all its modules ***[DAPP][ADR]***
Software architectural design of the full assembly of the Command and Control Computer and its individual components.	Design of the system software of the command and control computer and of all its modules ***[DAPP][CRBSD][ADR]***
Technical recommendations concerning integration of the software.	Achieved as planned ***[DAPP][CRBSD]***
Software development of substantial parts of the system software and its individual components	Software development of some configuration software computer items of the system software and their individual components ***[DAPP][CRBSD][ADR]***
Completion of the software development of the system software and its individual components with associated GUI	Full software development of the system software and its individual components ***[DAPP][CRBSD][ADR]***

1.4.4 Phased Array Design, Simulation and Development

The phased array was designed and developed by GRAS as responsible partner of this task.. The entire structure of the Master MFS microphone array and electronics consists in identically modules. The Master MFS Antenna has 512 microphones with a subdivision in 16 clusters (modules). Each Master MFS module has 16 microphones, a cable that transfer signal data to the A/D converter and another delivering power to the module.

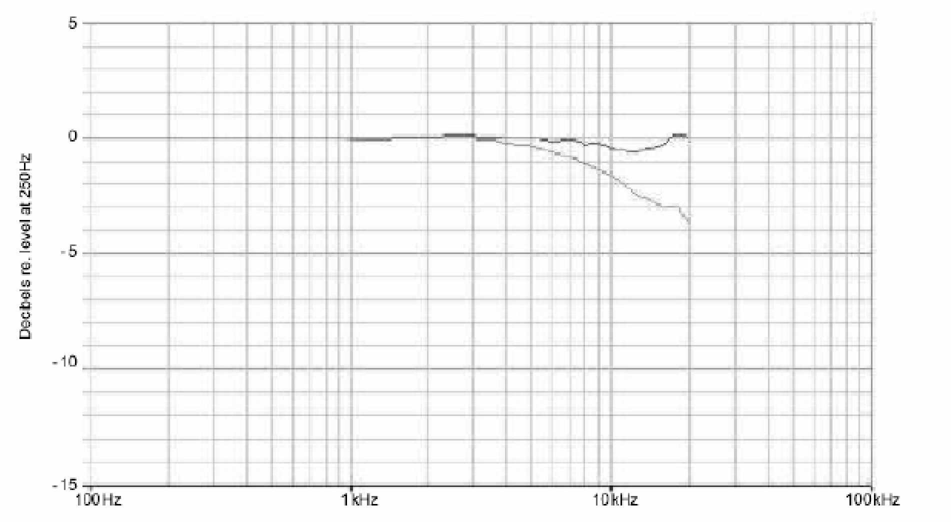


FIGURE 9 - GRAS 40PQ Microphone Typical Frequency Response.

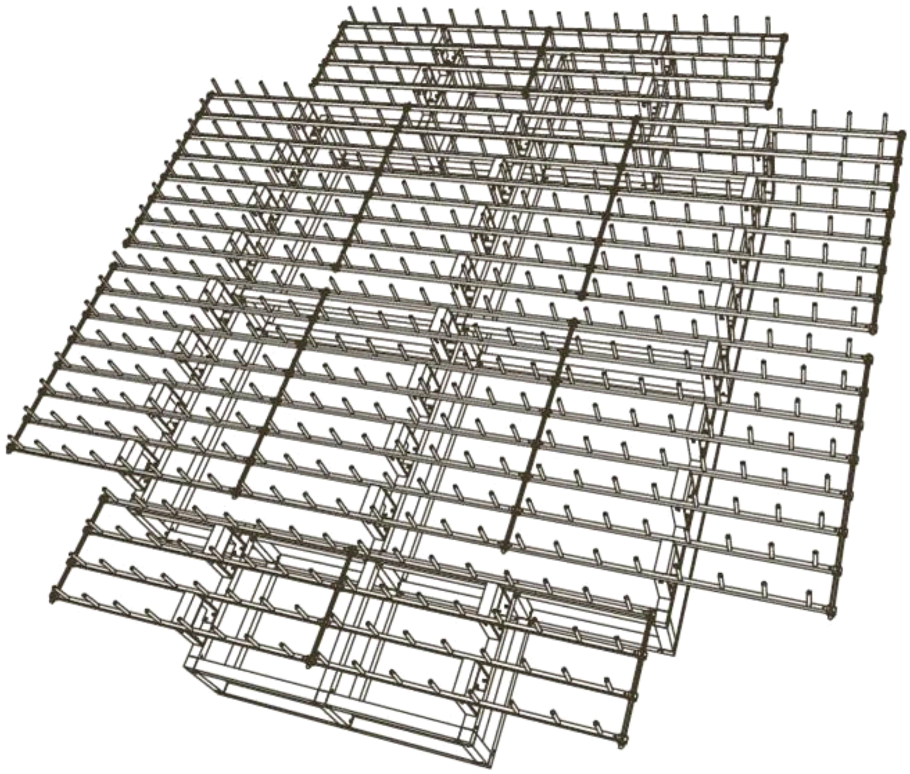


FIGURE 10 - Phased Array Antenna Architecture with 512 Microphones.

After laboratory testing of all microphones and modules with specialist tools, a field testing phase was carried out. The field testing performances were compared with the simulated performances and the expected numerical agreement between them is meant for the system validation both on the simulation level and on the field.

The antenna was completely assembled and installed in static (not rotating) position in the Fiumicino-Rome Airport. The aircraft was sensed by the antenna at a maximum distance of about 6 NM. 38 correlation filters were prepared in order to detect not only azimuth and elevation of the aircraft but also its range depending on the correlation filter that had maximum energy output. In July, 38 correlation filters were tabulated and input to the system. In the second month, system integration was performed. In September, the performance of the system equipped with 38 correlation filters (software algorithms) was tested filling the specific forms.

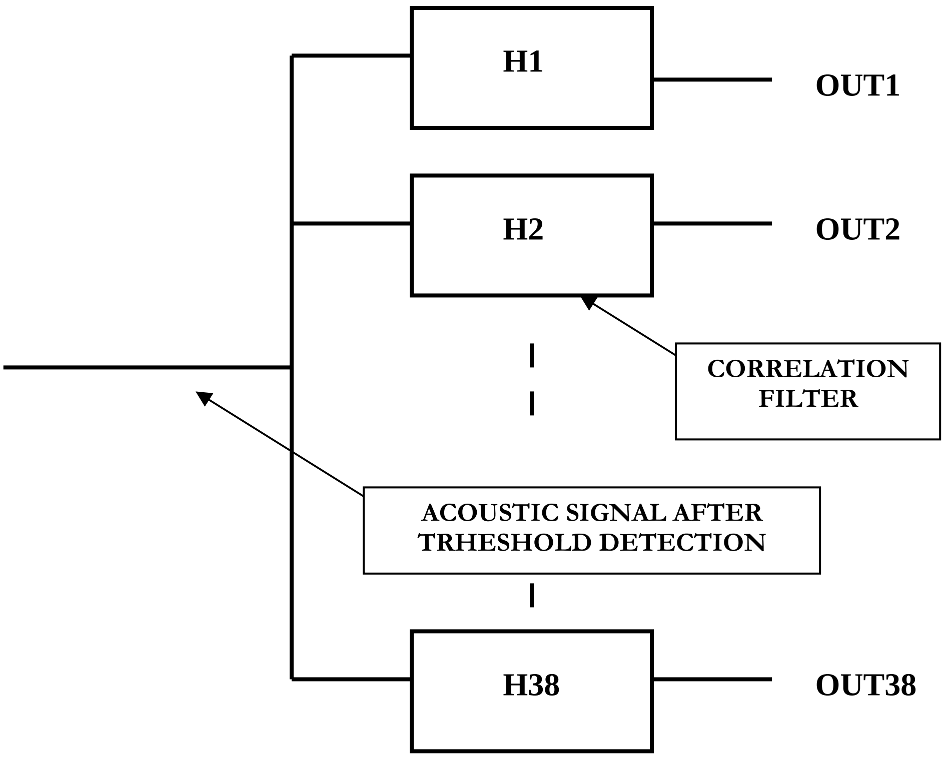


FIGURE 11 - Receiver Configuration – Correlation Filters Bank.

The aircraft position was determined on the basis of the maximum energy output of the above filter bank.

Such complex processing was performed off-line because the field testing was not preceded by a significant system integration phase (as initially planned with four months of system integration). Due to the large amount of data to process, the processing of 60 aircraft trajectories was already an ambitious target without fully automated and tested procedures. In the final system, this process will be fully automated but in this prototype version (system integration was not complete), this process was performed off-line. This limits the number of trajectories to be processed with reasonable effort to 60.

The start of the field testing activity was on the 1st of July 2005 and the conclusion in September 2005. The tests were carried out with one static antenna with reference to the landing scenario. The antenna was located near runway 16 Left of Fiumicino-Rome Airport.

The objectives were:

- development of a simulation to verify the phased array performance; phased array architectural design (FIGURE 9 and FIGURE 10);
- development of the Master Multi Function Sensor (MFS) without rotation electro-mechanics and dome;
- laboratory testing of the phased antenna array of 512 microphones;
- field testing of the phased antenna array of 512 microphones.

The following synoptic shows the achievements made:

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
Development of a simulation of verification of phased array performance; phased array architectural design.	Check of the phased array performance and beam-forming through simulation; Design of the phased array ***[DAPP] [UOR] [GRAS] [HYTEC] [ADR]***
Development of the Master MFS without rotation electro-mechanics and dome.	Check of the simulation parameters, selection of many construction parameters and components ***[GRAS][HYTEC]***
Development of the Master MFS without rotation electro-mechanics and dome	Full development of the phased antenna array of 512 microphones; ***[DAPP] [UOR] [GRAS] [HYTEC] [ADR]***
Laboratory testing of the phased antenna array of 512 microphones;	All microphones and modules were individually and carefully tested with specialist tools***[DAPP] [UOR] [GRAS] [HYTEC] [ADR]***
Field testing of the phased antenna array of 512 microphones;	Antenna prototype was tested on site at the Fiumicino-Rome Airport ***[DAPP] [UOR] [GRAS] [HYTEC] [ADR]***

1.4.5 Electronic Hardware Design and Development

HYTEC was the responsible partner for the electronic hardware. Design and development had the following objectives:

- hardware architectural design of the full assembly of the Master MFS and its individual components;
- hardware architectural design of the full assembly of the Command and Control Computer and its individual components;
- technical recommendations concerning in safety integration of the hardware (voltage ranges for the signal and synchronization interfaces);
- detailed description of the hardware architectures defined during the design of all hardware components;
- development of the custom cards of the data acquisition hardware;
- full development of the hardware of the custom computers.

The following synoptic shows the achievements made:

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
Hardware architectural design of the full assembly of the Master MFS and its individual components;	Design of the following hardware items: sensor management computer hardware, data acquisition hardware, wiring, and their modules in the Master MFS. ***[GRAS][HYTEC][ADR]***
Hardware architectural design of the full assembly of the Command and Control Computer and its individual components;	Design of the Command and Control Computer; Chosen of a standard PC architecture. ***[DAPP][GRAS][HYTEC][ADR]***
Technical recommendations concerning in safety integration of the hardware (voltage ranges for the signal and synchronization interfaces);	Achieved as planned ***[HYTEC][GRAS]***
Detailed description of the hardware architectures defined during the design of all hardware components;	Achieved as planned ***[DAPP] [GRAS] [HYTEC] [ADR]***
Development of electronic hardware	Design was checked out and main components were selected; Prototype realization ***[GRAS][HYTEC]***
Development of electronic hardware	Development of the custom cards of the data acquisition hardware ***[DAPP][GRAS][HYTEC][ADR]***
Full development of the hardware of the Custom computers*;*	The hardware electronics was completely developed ***[DAPP][GRAS][HYTEC][ADR]***

1.4.6 Dissemination

The dissemination activity was under the responsibility of the Department of Technical Physics at the University of Rome "La Sapienza". The main tools of the dissemination activity were:

- full design, development and monthly updating of the project website;
- publication of two scientific contributions to international conferences on acoustics.

The following synoptic shows the achievements made:

PLANNED OBJECTIVES	ACHIEVEMENTS MADE AND CONTRACTORS INVOLVED
Full project website design and development..	Preparation of a website monthly updated with all information about the project, currently available at the address: http://www.safe-airport.com ***[UOR]***
First contribution to an international conference of acoustics.	Contribution to the 148th Conference of the Acoustical Society of America in San Diego - California (US) with the paper: "Acoustic System for Aircraft Detection and Tracking based on Passive Microphones Arrays" on the 18th of November, 2004 ***[UOR]***
Second contribution to an international conference of acoustics.	Contribution to the 150th Conference of the Acoustical Society of America with NOISE-CON 2005 in Minneapolis - Minnesota (US) with the paper: "Outdoor Sound Propagation Effects on Aircraft Detection through Passive Phased Array Acoustic Antennas: 3D Numerical Simulations", 17-21 October, 2004 ***[UOR]***

1.4.7 Exploitation

The exploitation activity was prepared during the first 12 months through an Exploitation Plan, which was executed in the last period of the project. The implementation of the exploitation plan was carried out by GRAS and with the support of the Department of Technical Physics at the University of Rome "La Sapienza" during the last 9 months of the project.

The exploitation activity consisted in developing a PowerPoint® presentation which was sent via e-mail to all European Civil Aviation Administrations, main airports and aerospace industries.

In addition, a fax was also sent to all European Civil Aviation Administrations and airports to inform them about the SAFE-AIRPORT project.

1.4.8 Project Management

D'Appolonia S.p.A. was in charge of the activity of project management as SAFE-AIRPORT project coordinator.

The following are among the main tasks and objectives:

- preparation of the progress reports;
- preparation of the final reports, includine a final document, along with a journalistic style version, a final plan for using and disseminating knowledge, a report on actions taken to raise public participation and awareness;
- organization of technical meetings;
- intellectual property management;
- financial management.

This task involved all project activities coordination, documents preparation and the solution of some needs expressed by consortium partners.

In addition, within this activity are comprises the internal project review and the organization of the review meeting chaired by DAPP in Rome. All main items of the first reporting period were discussed together with all partners along with the preparation of the last months of the project.

A review meeting for the European Commission was also held in Brussels.

1.5 End Results

The following items were fully achieved in the first year:

- the specification and design of the system and of the system simulation;
- the complete design and development of the project website;
- publication of a scientific paper presented at a Conference of the Acoustical Society of America (ASA).

By the end of SAFE-AIRPORT project also the following items were achieved:

- the full development of the Master MFS (Multi-Function Sensor) without rotation and dome; the Command and Control Unit with associated GUI;
- the system simulation;
- the phased array field testing;

- the exploitation was planned and implemented;
- the publication of a second scientific paper.

In the first 12 months we contributed to the 148th Conference of the Acoustical Society of America (ASA) held in Sand Diego, California (US) with the paper: "Acoustic System for Aircraft Detection and Tracking based on Passive Microphones Arrays", which was presented on the 18th of November, 2004.

This publication focused on several issues about the SAFE-AIRPORT system electronics and acoustics. The array's spatial selectivity was discussed aiming to optimize beam-forming design according to spectral properties of common jet aircrafts. In particular, the influence of the number and the geometric distribution of microphones were shown in function of the target's acoustic frequency and signal to noise ratio sensitivity. The system's range was roughly estimated at different working frequencies and for different positions of the aircraft on the horizon. The effect of wind gradients on the estimation of the aircraft position was also modeled and computer simulations showing consequent deviation of acoustic waves were performed. Finally, possible developments in antenna design, such as the use of three fixed planar-arrays in tetrahedral configuration instead of one rotating planar-array, were evaluated showing expected advantages.

In the last 9 months another scientific paper titled "Outdoor Sound Propagation Effects on Aircraft Detection through Passive Phased Array Acoustic Antennas: 3D Numerical Simulations" was published as contribution to the 150th Meeting of the Acoustical Society of America (ASA) with NOISE-CON 2005 in Minneapolis, Minnesota (US), 17-21 October 2005.

In particular, this second paper focused more carefully than the previous one on the outdoor propagation of sound waves in the atmosphere and its influence on the system detection efficiency.

The effects of air temperature and wind gradients on aircraft tracking were analyzed and modeled. Correction of antenna output data errors on aircraft location due to acoustic rays' deviation in 3D layered atmosphere model was studied. Algorithms for sound refraction-correction were implemented according to the Snell's law. Numerical simulations were performed using several temperature and wind profiles according to common and critical meteorological conditions.

Aircraft location was predicted through 3D acoustic rays' triangulation methods taking into account variation in speed of sound waves along rays' paths toward each antenna.

The system range was also assessed in detail considering aircraft noise spectral emission. Outdoor acoustic attenuation was evaluated in function of noise frequency and of atmospheric conditions in terms of air temperature and humidity. Since the speed of common airplanes is not negligible respect to sound speed during typical airport operations such as takeoff and approaching, the influence of the Doppler Effect on range calculation was also considered and most critical scenarios were simulated.

This second paper also discussed other important aspects of sound propagation such as time delay of acoustic signals and acoustic shadows zone estimation.

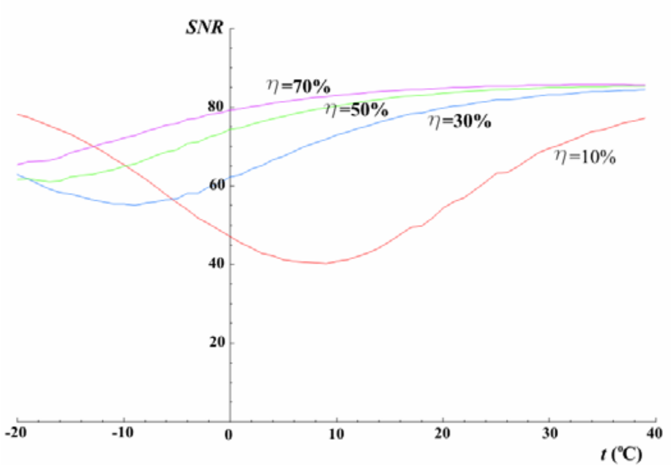


FIGURE 12 - Simulated Antenna Signal-to-Noise Ratio (*SNR*) at ATZ Border vs. Air Temperature *t* in Function of the Relative Humidity □

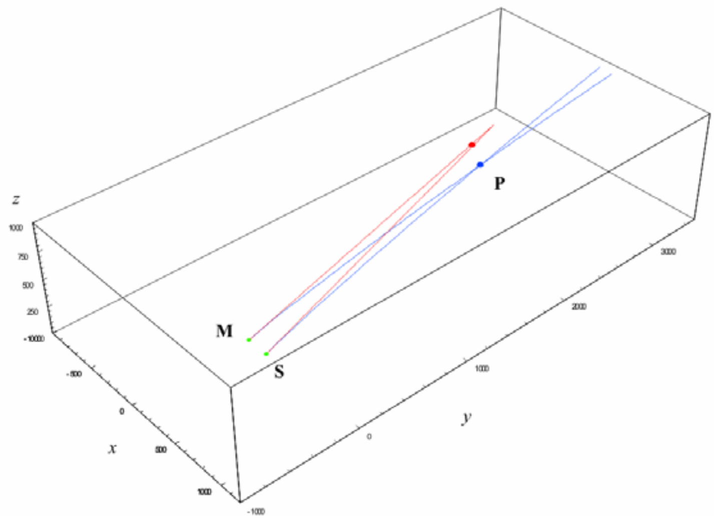
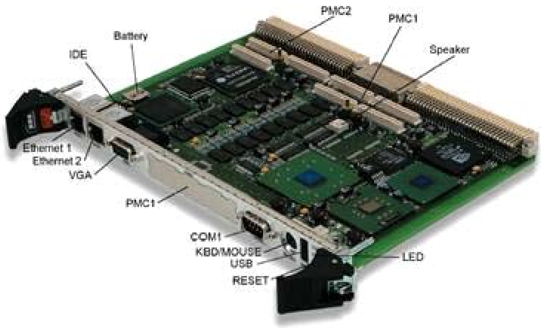


FIGURE 13 - 3D Simulation of Corrected Aircraft Position P (blue point) Taking Into Account Deviated Acoustic Rays (Blue Rays) for Air Temperature and Wind Gradients. Uncorrected Aircraft Position is Shown in Red.

As regarding the field testing results, it was found out that the maximum detection distance for landing aircrafts was about 6 nautical mile. The no-detection rate was very low for distances less than 5 nautical miles (8.9%), but it deteriorated for distances larger than 5 nautical miles (22%). This performance could be increased by replacing the fan with a less noisy dissipating concept and equipping the phased array antenna with a rear protection in order to achieve a better acoustic insulation from noise coming from backward. Both measures would help to reduce significantly the background noise, increasing correspondingly the range of the system.

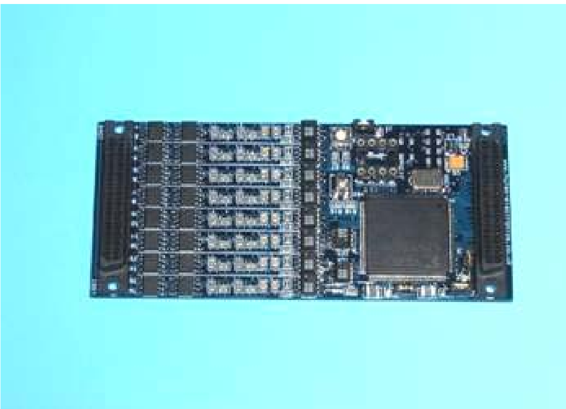
Concerning the operation of the bank of correlation filters, which resulted useful to detect the range, they performed well at a low-medium distance (only 18% of failures in discrimination of range for distances less than 5 nautical miles), but they showed a high rate of errors for larger distances (33,7% of failures in discrimination of range for distances higher than 5 nautical miles).

1.6 Project Photo Gallery



Sensor Management CPU

Sensor Management DSP



Custom A/D Converter Board

Sensor Management Rack

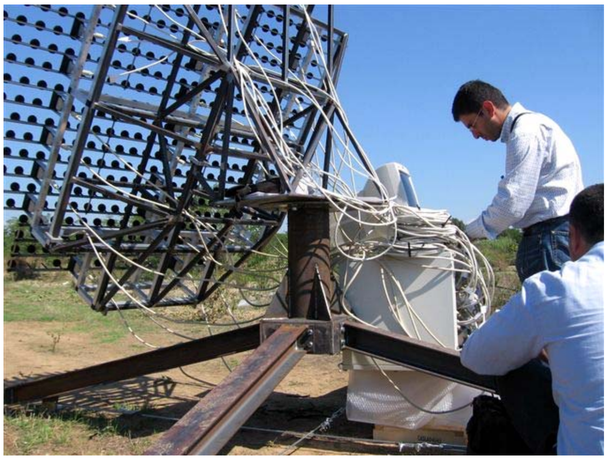
GRAS 40PQ Microphone

Antenna Manufacturing

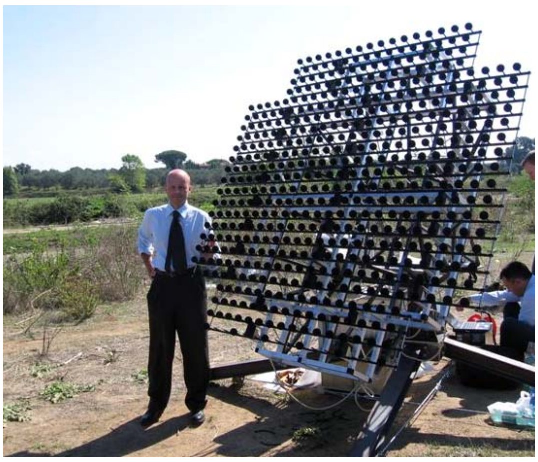
Instrumentation Transportation and Power Supply

Antenna Assembling On Site

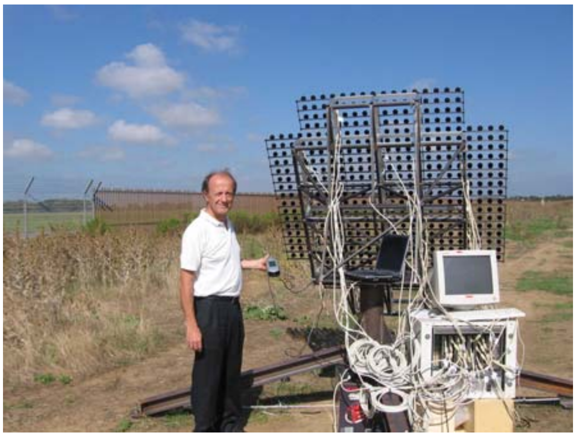
Antenna Prototype mounted on Site



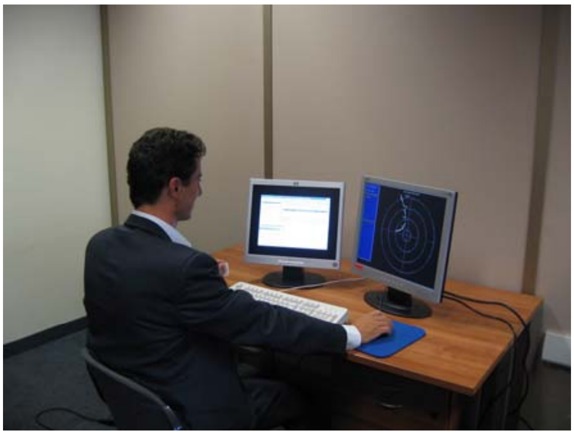
Electronic Hardware and Cables Installation



Antenna Prototype Ready for Field Testing



Instrumentation during Field Testing Measurements



Command & Control Computer Operator

System Graphic User Interface

1.7 Logo and Project Website

http://www.safe-airport.com

2 ANNEX I – PLAN FOR USING AND DISSEMINATING THE KNOWLEDGE

2.1 SECTION 1 – Exploitable Knowledge and Its Use

Standing the definition of "Knowledge", that means the results, including information, whether or not they can be protected, which are yielded by direct actions and indirect actions, as well as copyrights or rights pertaining to such information following applications for, or the issue of patents, designs, plant varieties, supplementary protection, Partner Nr. 1 **[DAPP]**, as prime contractor of the project, assumed the responsibility of the distribution of the knowledge sorted from the defined outputs **[OUT_01,…, OUT_10]** within all consortium partners, following the statements regarding knowledge and intellectual properties, that will be defined in the Consortium Agreement Form and within the statements of **FP6 IPR** (Intellectual Protection Rights) rules (Regulation: Art. 21 to 28[1]), to be prepared by Partner Nr. 1 **[DAPP]**, in agreement with the other partners, before signing the contract with the European Commission.

Regarding the different outputs each partner is the owner of the specific output knowledge and has the responsibility to provide the knowledge acquired to Partner Nr. 1 **[DAPP]** for further distribution within the other Partners, to ensure the correct information sharing needed to *SAFE-AIRPORT* project completion and following the statements of Consortium Agreement Form. In particular, the main knowledge owners and beneficiaries for each project Output can be resumed in the following table:

KNOWLEDGE ID	RELATED PROJECT OUTPUT	PARTECIPANTS INVOLVED	DESCRIPTION
KN_01	**MFS Managing SW D&D Capability [OUT_08]**	***DAPP***	*Knowledge on design and developing of modular software for multifunctional acoustic sensors management in C language.*
KN_02	**C2 and GUI SW D&D Capability [OUT_09]**	***CRBSD***	*Knowledge on capability to design and developing of modular software for Command and Control Unit management and GUI interface in C language and in Windows NT® environment to show track data of acoustic tracking systems.*
KN_03	**Microphone Phased Array D&D Capability [OUT_10]**	***GRAS***	*Knowledge on design and developing of acoustic phased array with more than 500 microphones.*
KN_04	**SMC D&D Capability [OUT_11]**	***HYTEC***	*Knowledge on design and developing of customised VME Bus computers for the management of multifunctional*

[1] Regulation of the European Parliament and the Council concerning the rules for the participation of undertakings, research centres and universities in and for the dissemination of research results for the implementation of the European Community Sixth Framework Programme (2002-2006). Not yet published.

KNOWLEDGE ID	RELATED PROJECT OUTPUT	PARTECIPANTS INVOLVED	DESCRIPTION
			acoustic sensors.
KN_05	**System Simulation SW D&D Capability [OUT_12]**	***UOR***	*Knowledge on design and developing of simulations for complex acoustic tracking systems.*

TABLE 1 – Knowledge – Project Outputs Correspondence

For those outputs in which knowledge is reached jointly, there is e a joint ownership of property.

Distribution of knowledge outside the Consortium is managed through the Dissemination Plan entrusted to Partner Nr. 2 **[UOR]**, taking care that this dissemination didn't affect adversely either IPR FP6 Regulation and the core contract or its use and following the statements included in the Consortium Agreement Form and the procedure related to the European Commission constraint described in the Dissemination Plan for the Use of Project Outputs.

Partner Nr. 2 **[UOR]** will ensure that the knowledge is disseminated within the period laid down by the Community -2 years following the draft model contract.

IP (Intellectual Property) Management Plan is carried on by Partner Nr.1 **[DAPP]** and defined, with the participation of all the partners, during Consortium Agreement Form definition, following the statements of FP6 IPR rules for participation.

In particular attention is focused on:

- **Pre-existing know-how**: defined as the information, licences and user rights already held by the participants prior to the contract and granted for the execution of the project and use of the results (Art 2.21 Regulation);
- **Acquired knowledge:** Project Outputs (including information) and rights on these results capable of industrial application and related marketing.

The rules for the distribution of Pre-existing know-how within the Consortium partners for the execution of the project and for the direct or indirect utilisation of the knowledge in research activities or for the purposes of exploitation which means the utilisation of the knowledge for creating and marketing a product or process or for creating and providing a service of project outputs, including the financial conditions, was defined during Consortium Agreement Form definition under Partner Nr. 1 **[DAPP]** supervision.

Possible Project acquired intellectual properties beneficiaries can be resumed in the following table:

INTELLECTUAL PROPERTY ID	RELATED PROJECT OUTPUT	PARTECIPANT INVOLVED	DESCRIPTION
IP_01	**MFS Managing SW [OUT_01]**	***DAPP***	*Copyright on acoustic sensor management software.*
IP_02	**C2 and GUI SW [OUT_02]**	***CRBSD***	*Copyright on GUI and Command & Control Software for acoustic tracking applications*
IP_03	**Prototype of Microphone Phased Array [OUT_03]**	***GRAS***	*Patent on microphone phased arrays with high beam directivity.*
IP_04	**SMC Prototype [OUT_04]**	***HYTEC***	*Patent on high performance VME computers for the management of multifunction acoustic sensor.*
IP_05	**System Simulation SW [OUT_05]**	***UOR***	*Copyright on simulation software developed for the modelisation on complex acoustic tracking system.*

TABLE 2 – Intellectual Property – Project Outputs Correspondence

If acquired knowledge will be capable of industrial or commercial application**,** its owner shall provide for its adequate and effective protection in conformity with relevant legal provisions, the contract and the consortium agreement, and having due regard to the legitimate interests of the participants concerned.

The rules for the acquired knowledge within the Consortium partners for the execution of the project and for the direct or indirect use of the knowledge in research activities *or* for the purposes of exploitation which means the utilisation of the knowledge for creating and marketing a product or process or for creating and providing a service of project outputs, including the financial conditions, was defined during Consortium Agreement Form definition under Partner Nr. 1 **[DAPP]** supervision and following IPR FP6 Regulation and the core contract.

Acquired knowledge protection scheduling, was related to the knowledge produced during Work Plan development and will follow the Work Plan scheduling related to each Output.

The main Project Outputs were reached through the completion of several innovations related activities that can be summarised in the following table:

INNOVATION ID	RELATED PROJECT OUTPUT	PARTICIPANT INVOLVED	INNOVATION DESCRIPTION
INN_01	**MFS Managing SW D&D Capability [OUT_06]**	***DAPP***	*Design of algorithms for the aircraft identification based on acoustic spectrum data and pre-scheduling, scheduling and sensor command algorithms needed to manage multifunctional acoustic sensors.*
INN_02	**C2 and GUI SW D&D Capability [OUT_07]**	***CRBSD***	*Design of command & control algorithms needed to manage a track database and classify threat situations.*
INN_03	**Microphone Phased Array D&D Capability [OUT_08]**	***GRAS***	*Design and development of microphone arrays with high beam directivity.*
INN_04	**SMC D&D Capability [OUT_09]**	***HYTEC***	*Design of high performance VME computers for the management of multifunction acoustic sensor.*
INN_05	**System Simulation SW D&D Capability [OUT_10]**	***UOR***	*Design and development of simulation models for complex acoustic tracking systems with embedded environmental and meteorological conditions adjustments.*

TABLE 3 – Innovation – Project Outputs Correspondence

The table shows the belongings of each innovation item with the relative Work Project.

A Task Leader was appointed by each WP Responsible to ensure the completion of each innovation activity.

Acquired knowledge, coming from these innovation activities, protection scheduling, was related to the knowledge produced during Work Plan development and followed the Work Plan scheduling related to each Output.

EXPLOITABLE KNOWLEDGE (DESCRIPTION)	EXPLOITABLE PRODUCT (S) OR MEASURE(S)	SECTOR(S) OF APPLICATION	TIMETABLE FOR COMMERCIAL USE	PATENTS OR OTHER IPR PROTECTION	OWNER & OTHER PARTNER(S) INVOLVED
KN_01: MFS Managing SW D&D Capability [OUT_06]	Consultancy Services	1. Safety and Security; 2. Aeronautics.	2007 2008	N.A.	***DAPP***
KN_02: C2 and GUI SW D&D Capability [OUT_07]	Consultancy Services	1. Safety and Security; 2. Aeronautics.	2007 2008	N.A.	***CRBSD***
KN_03: Microphone	Consultancy Services	1. Safety and Security;	2007	N.A.	***GRAS***

EXPLOITABLE KNOWLEDGE (DESCRIPTION)	EXPLOITABLE PRODUCT (S) OR MEASURE(S)	SECTOR(S) OF APPLICATION	TIMETABLE FOR COMMERCIAL USE	PATENTS OR OTHER IPR PROTECTION	OWNER & OTHER PARTNER(S) INVOLVED
Phased Array D&D Capability [OUT_08]		2. Aeronautics.	2008		
KN_04: SMC D&D Capability [OUT_09]	Consultancy Services	1. Safety and Security; 2. Aeronautics.	2007 2008	N.A.	***HYTEC***
KN_05: System Simulation SW D&D Capability [OUT_10]	Consultancy Services	1. Safety and Security; 2. Aeronautics.	2007 2008	N.A.	***UOR***
IP_01: MFS Managing SW [OUT_01]	Software	1. Safety and Security; 2. Aeronautics.	2007 2008	*Copyright on acoustic sensor management software.*	***DAPP***
IP_02: C2 and GUI SW [OUT_02]	Software	1. Safety and Security; 2. Aeronautics.	2007 2008	*Copyright on GUI and Command & Control Software for acoustic tracking applications*	***CRBSD***
IP_03: Prototype of Microphone Phased Array [OUT_03]	Hardware	1. Safety and Security; 2. Aeronautics.	2007 2008	*Patent on microphone phased arrays with high beam directivity.*	***GRAS***
IP_04: SMC Prototype [OUT_04]	Hardware	1. Safety and Security; 2. Aeronautics.	2007 2008	*Patent on high performance VME computers for the management of multifunction acoustic sensor.*	***HYTEC***
IP_05: System Simulation SW [OUT_05]	Software	1. Safety and Security; 2. Aeronautics.	2007 2008	*Copyright on simulation software developed for the modelisation on complex acoustic tracking system.*	***UOR***

TABLE 4 – Exploitable Knowledge and It Use - Overview

EXPLOITABLE RESULT	DESCRIPTION	PARTNER(S) INVOLVED	HOW THE RESULT MIGHT BE EXPLOITED	FURTHER ADDITIONAL RESEARCH AND WORK	IPR MEASURES	COMMERCIAL CONTACS	POTENTIAL IMPACT
KN_01: MFS Managing SW D&D Capability [OUT_06]	*Knowledge on design and developing of modular software for multifunctional acoustic sensors management in C language.*	***DAPP***	Product (Consultancy Service) with promotion on individual basis [DAPP].	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	N.A.	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*DAPP Personnel Increasing with the Commercialisation of the Product.*
KN_02: C2 and GUI SW D&D Capability [OUT_07]	*Knowledge on capability to design and developing of modular software for Command and Control Unit management and GUI interface in C language and in Windows NT® environment to show track data of acoustic tracking systems.*	***CRBSD***	Product (Consultancy Service) with promotion on individual basis [CRBSD]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	N.A.	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*CRBSD Personnel Increasing with the Commercialisation of the Product.*
KN_03: Microphone Phased Array D&D Capability [OUT_08]	*Knowledge on design and developing of acoustic phased array with more than 500 microphones.*	***GRAS***	Product (Consultancy Service) with promotion on individual basis [GRAS]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	N.A.	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*GRAS Personnel Increasing with the Commercialisation of the Product.*
KN_04: SMC D&D Capability [OUT_09]	*Knowledge on design and developing of customised VME Bus computers for the management of multifunctional acoustic sensors.*	***HYTEC***	Product (Consultancy Service) with promotion on individual basis [HYTEC]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	N.A.	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*HYTEC Personnel Increasing with the Commercialisation of the Product.*
KN_05: System Simulation SW D&D Capability [OUT_10]	*Knowledge on design and developing of simulations for complex acoustic tracking systems.*	***UOR***	Product (Consultancy Service) with promotion on individual basis [UOR]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	N.A.	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*UOR Personnel Increasing with the Commercialisation of the Product.*
IP_01: MFS Managing SW [OUT_01]	*A multifunctional [CSCI-SP, CSCI-DH and CSCI-SC] sensor managing software developed in C Language and conform to FAA-STD-026 standards. Software will be completely or partially portable on other tracking acoustical systems even if with different HW configuration*	***DAPP***	Product (Software) with promotion on individual basis [DAPP]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	*Copyright on acoustic sensor management software.*	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*DAPP Personnel Increasing with the Commercialisation of the Product.*
IP_02: C2 and GUI SW	*The Software will be completely or*	***CRBSD***	Product (Software) with	- SAFE-AIRPORT	*Copyright on GUI and*	*SECTION 3(Italian*	*CRBSD Personnel Increasing with the*

EXPLOITABLE RESULT	DESCRIPTION	PARTNER(S) INVOLVED	HOW THE RESULT MIGHT BE EXPLOITED	FURTHER ADDITIONAL RESEARCH AND WORK	IPR MEASURES	COMMERCIAL CONTACS	POTENTIAL IMPACT
[OUT_02]	*partially portable on other tracking acoustical systems even if with different HW configuration: - Command & Control management software [CSCI-C2] developed in C Language and conform to FAA-STD-026 standards; - User graphics interface software [CSCI-GUI] based on Windows NT® operative system to get track data visualization on two monitors. Acquired tracks are shown on the first monitor, while the second monitor is used to perform system queries starting from a table representation of track data. The second monitor is used also to signal collision risk situations and whether environmental noise, measured during search and tracking activities, exceeded noise limits.*		promotion on individual basis [CRBSD]	Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	*Command & Control Software for acoustic tracking applications*	*Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*Commercialisation of the Product.*
IP_03: Prototype of Microphone Phased Array [OUT_03]	*One high directivity planar microphone phased array*	***GRAS***	Product (Hardware) with promotion on individual basis [GRAS]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	*Patent on microphone phased arrays with high beam directivity.*	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*GRAS Personnel Increasing with the Commercialisation of the Product.*
IP_04: SMC Prototype [OUT_04]	*Computer customized to manage a multifunctional acoustic sensor, build with VME Bus solutions. Electromagnetic shielding solutions will be in conformity with avionic needs. The Computer can be used, changing some customisations, for different multifunctional sensors.*	***HYTEC***	Product (Hardware) with promotion on individual basis [HYTEC]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the end of STEP 2.	*Patent on high performance VME computers for the management of multifunction acoustic sensor.*	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*HYTEC Personnel Increasing with the Commercialisation of the Product.*
IP_05: System Simulation SW [OUT_05]	*System simulation software founded on a Montecarlo code random generator [CSCI-ASIM e CSCI-SCEN] developed in FORTRAN 77 in*	***UOR***	Product (Software) with promotion on individual basis [UOR]	- SAFE-AIRPORT Project STEP 2; - Two Year of Product Industrialisation at the	*Copyright on simulation software developed for the modelisation on complex acoustic tracking system.*	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*	*UOR Personnel Increasing with the Commercialisation of the Product.*

EXPLOITABLE RESULT	DESCRIPTION	PARTNER(S) INVOLVED	HOW THE RESULT MIGHT BE EXPLOITED	FURTHER ADDITIONAL RESEARCH AND WORK	IPR MEASURES	COMMERCIAL CONTACS	POTENTIAL IMPACT
	conformity with FAA-STD-026 standards. The software can be used integrally or partially for numerical simulations of other tracking systems with some adaptations			end of STEP 2.			

TABLE 5 – Short Text per Exploitable Result

2.2 SECTION 3 – Dissemination of Knowledge

Dissemination of system specific information and work progress uses the following diffusion tools:

- project website [DIS_01];
- information documentation envoy [DIS_02];
- papers publication on specialised journals [DIS_03];
- participation to International ASA (International Commission for Acoustics) conference [DIS_04].

Website was carried out within the first six months (T0 + 6 Months) and dissemination timing was as following:

- monthly revision of the website starting from the sixth month from project kick-off meeting (T0) and for all the project duration;
- the envoy of project information documentation was revised every three months from project T0 and for all the project duration;
- a paper publication on a specialised journal every year, revised every three months and for all the project duration;
- presentation of a participation request for a yearly international acoustics conference, organised by ASA.

Dissemination management was entrusted to Department of Technical Physics, University of Rome "La Sapienza" **[UOR]** represented by Donatella Rondinella (MBA - International Marketing).

Dissemination occurred anyway according to the following constraint:

"A participant may publish or allow the publication, on whatever medium, of data concerning knowledge it owns or knowledge obtained during work in connection with co-operative or collective research projects. However, if publication can affect the protection of that knowledge, it is not allowed. Any planned publication should be made according to the following procedure:

- *the Commission and the other participants in the project shall be given prior written notice of any planned publication;*
- *a copy of such data shall, on request, be made available to them within 30 days of the request.*

The Commission and the other participants may object to the publication within a period of 30 days from receipt of data, if they consider that the protection of their knowledge could thereby be adversely affected."

In the following table is shown a synthesis of the performed dissemination.

PLANNED / ACTUAL DATES	TYPE	TYPE OF AUDIENCE	COUNTRIES ADDRESSED	SIZE OF AUDIENCE	PARTNER RESPONSIBLE / INVOLVED
6th June 2004 / 6th June 2004	Project Website **[DIS_01]**	General Public	All the World Countries (Internet Users)	World Wide Web.	UOR / All the Partners.
30th April 2005 / 30th April 2005	Information documentation envoy **[DIS_02]**	Airports	Italy	Italy	UOR / GRAS
18th November 2004 / 18th November 2004	Papers publication on specialised journals **[DIS_03]**	Research	All the World Countries	Acoustic Research World	UOR / DAPP
30th August 2005	Completion of the Exploitation **[DIS_02]**	Airports, Civil Aviation Administrations (CAA), Industry	European Union Countries	European Airports and CAA Industries in the World	UOR / GRAS
21st September 2005	Project Website Update with Field Testing Photo Gallery and New Scientific Paper **[DIS_01]**	General Public	All the World Countries (Internet Users)	World Wide Web.	UOR
18th November 2004 / 18th November 2004	Participation ASA conference **[DIS_04]**	Research	All the World Countries	Acoustic Research World	UOR
17th October 2005 / 21st October 2005	Participation ASA conference **[DIS_04]**	Research	All the World Countries	Acoustic Research World	UOR

TABLE 6 – Dissemination of Knowledge - Overview

The scientific papers are in the ANNEX II. The address of the Project Website is: http://www.safe-airport.com..

2.3 SECTION 3 – Publishable Results

The exploitation strategy was carried out through the execution of each planned action as follows:

- ACTION 1: a PowerPoint® presentation showing the main features of the SAFE-AIRPORT Project was developed;
- ACTION 2: a list of aerospace industries to be contacted was developed. The list is organised in the two contact sessions in order to distribute gradually the task during the development of ACTION 5 (see below). The companies shown in TABLE 7 refer to the first 12 month (first contact session). The remaining companies (TABLE 8 are organised into a separate list for the second contact session to be contacted in 2005 by the end of the SAFE-AIRPORT project;
- ACTION 3: the same PowerPoint® presentation as described in ACTION 1 was used to accomplish this action. Such a presentation was sent to the aerospace companies by e-mail along with the fact sheet;
- ACTION 4: the same PowerPoint® presentation as in ACTION 1 and ACTION 3 was shown at a meeting held at ASSOAEROPORTI in Rome, on Tuesday, 9th June 2005. In addition, Italian airport management companies were also sent a fax with an involvement invitation to take part in a future project development;
- ACTION 5: according to the list developed in ACTION 2, aerospace companies were sent a fact sheet by e-mail.

Finally, also the main European Civil Aviation Administrations and several European airport management companies were sent the same fax as in ACTION 4 in order to extend the involvement to other EU countries:

- European Civil Aviation Administrations;
- European airport management companies:
  - Airports in Austria;
  - Airports in Belgium;
  - Airports in Cyprus;
  - Airports in Czech Republic;
  - Airports in Denmark;
  - Airports in Estonia;
  - Airports in Finland;
  - Airports in France;
  - Airports in Germany;
  - Airports in Greece;

- o Airports in Irish Republic;
- o Airports in Latvia;
- o Airports in Lithuania;
- o Airports in Luxembourg;
- o Airports in the Netherlands;
- o Airports in Poland;
- o Airports in Portugal;
- o Airports in Slovakia;
- o Airports in Spain;
- o Airports in Sweden;
- o Airports in United Kingdom.

ID	Aerospace Industries –FIRST CONTACT SESSION
1	AAI Corporation
2	Advanced Products Corporation
3	Air Liquide-Medal L.P.
4	Allfast Fastening Systems, Inc.
5	American Pacific Corporation
6	Analytical Graphics, Inc.
7	ACTI
8	Argo-Tech Corporation
9	Armor Holdings Aerospace & Defense, Inc.
10	ATK
11	AUSCO, Inc.
12	Aviall, Inc.
13	B&E Precision Aircraft Components
14	BAE SYSTEMS
15	Barnes Aerospace
16	B.H. Aircraft Company, Inc.
17	The Boeing Company
18	Celestica Corporation
19	Click Bond, Inc.
20	Cobham Aerospace Systems Group
21	Computer Sciences Corporation
22	Crane Aerospace & Electronics
23	Cubic Corporation
24	Curtiss-Wright Corporation
25	Dassault Falcon Jet Corporation
26	Doncasters, Inc.
27	DRS Technologies, Inc.
28	Ducommun Incorporated
29	DuPont Company
30	Eaton Aerospace LLC

ID	Aerospace Industries –FIRST CONTACT SESSION
31	Eclipse Aviation
32	EDO Corporation
33	EDS
34	EFW Inc.
35	Embraer Aircraft Holding Inc.
36	Emhart Teknologies
37	Erickson Air-Crane Incorporated
38	ESIS, Inc.
39	Esterline Technologies
40	Exostar LLC
41	Federation Inc.
42	Flight Safety International Inc.
43	General Atomics Aeronautical Systems, Inc.
44	General Dynamics Corporation
45	General Electric
46	GKN Aerospace, Aerostructures
47	Goodrich Corporation
48	W. L. Gore & Associates, Inc.
49	Harris Corporation
50	HEICO Corporation
51	Hexcel Corporation
52	HITCO Carbon Composites
53	Honeywell
54	IBM Corporation
55	ITT Industries
56	Defense and Electronics
57	Kaman Aerospace Corporation
58	Kistler Aerospace Corporation
59	L-3 Communications Corporation
60	Laser Technology Inc.
61	LMI Aerospace Inc.
62	Lockheed Martin Corporation
63	3M Company
64	Martin-Baker America Inc.
65	McKechnie Aerospace
66	MOOG Inc.
67	Natel Engineering Co. Inc.
68	National Machine Group
69	National Technical Systems
70	Northrop Grumman Corporation
71	NYLOK Corporation
72	Omega Air, Inc.
73	Oracle USA, Inc.
74	Orbital Sciences Corporation
75	Parker Aerospace
76	PerkinElmer, Inc.
77	Pinkerton Government Services, Inc.
78	Proficiency Inc.
79	The Purdy Corporation
80	Raytheon Company
81	Remmele Engineering, Inc.

ID	Aerospace Industries –FIRST CONTACT SESSION
82	Rockwell Collins
83	Rolls-Royce North America Inc.
84	RTI International Metals, Inc.
85	Science Applications International Corporation
86	Shaw Aero Devices, Inc.
87	Silicon Graphics, Inc. SITA
88	SM&A
89	Smiths Aerospace Actuation Systems Los Angeles
90	Space Exploration Technologies Corporation
91	Stellex Aerostructures, Inc.
92	Suntron Corporation
93	Swales Aerospace
94	Teleflex Inc.
95	Textron Inc.
96	Titan Corporation
97	Triumph Group, Inc.
98	Turbine Engine Components Technologies Corp.
99	United Technologies Corporation
100	Pratt & Whitney
101	Sikorsky
102	Hamilton Sundstrand
103	Vought Aircraft Industries, Inc.
104	Woodward Governor Company

TABLE 7 - Aerospace Industries – First Contact Session

ID	Aerospace Industries – SECOND CONTACT SESSION
1	A.E. Petsche Company
2	Acromil Corporation
3	ADI American Distributors, Inc.
4	Aerospace Fabrications of GA, Inc.
5	Air Industries Machining Corporation
6	Airborn Operating L.P.
7	Alcoa Fastening Systems
8	Alken Industries Inc.
9	Allen Aircraft Products, Inc.
10	AM Castle & Company
11	Ametek Hughes-Treitler
12	Arkwin Industries, Inc.
13	Arrow/Zeus Electronics, div. of Arrow Electronics
14	A & S Tribal Industries
15	Astronautics Corporation of America
16	AVChem, Inc
17	Avexus, Inc.
18	Avionics Specialties, Inc.
19	Avnet Electronics Marketing
20	B&B Manufacturing Company, Inc
21	Banneker Industries, Inc
22	Brogdon Tool & Die, Inc

ID	Aerospace Industries – SECOND CONTACT SESSION
23	Brush Wellman Inc
24	BTC Electronic Components
25	Burton Industries Aerospace Heat Treating Inc.
26	California Manufacturing Technology Consulting
27	Capo Industries Inc.
28	Celltron Inc
29	CFI-PAC Foundries
30	Chandler/May, Inc.
31	Cherokee Nation Distributors
32	Cincinnati Machine, A Unova Company
33	Circle Seal Controls, Inc.
34	CMC Electronics
35	Coalition Solutions Integrated, Inc.
36	Cohesia Corporation
37	Compass Aerospace Corporation
38	Corfin Industries, LLC
39	CPI Aerostructures, Inc.
40	Cytec Engineered Materials
41	Dassault Systems of America
42	Data Conversion Laboratory, Inc.
43	Dayton T. Brown Inc.
44	Designed Metal Connections
45	Dimension4, Inc
46	DynaBil Industries, Inc.
47	East West Technology
48	Electronic/Fasteners, Inc.
49	EMS Technologies, Inc.
50	Enginetics Corporation
51	ENSCO, Inc
52	Exotic Metals Forming Company LLC
53	Fastener & Hose Technology, Inc.
54	Mid-State Aerospace, Inc.
55	Fenn Technologies
56	The Ferco Group
57	Frontier Electronic Systems Corporation
58	G.S. Precision, Inc.
59	Gardner Aerospace
60	GEAR Software
61	Greene, Tweed & Co.
62	H&S Swansons' Tool Company
63	HAAS TCM
64	Harvard Custom Manufacturing
65	HDL Research Lab, Inc
66	Heart of Georgia Metal Crafters
67	Heartland Precision Fasteners
68	Aerospace Plating Company
69	Heizer Aerospace
70	Hi-Temp Insulation Inc
71	Hobart Machined Products Inc
72	Hughes Bros. Aircrafters, Inc
73	iBASEt

ID	Aerospace Industries – SECOND CONTACT SESSION
74	Industrial Metals Intl. Ltd.
75	Ingersoll Machine Tools, Inc
76	Inmedius
77	Jabil Defense & Aerospace
78	Jazz Semiconductor
79	KPMG LLP-Risk Advisory Services
80	Kulite Semiconductor Products, Inc
81	L. Gordon Packaging
82	LaBarge, Inc.
83	Lattice 3D
84	Lockmasters Security Institute
85	M/A-COM, Inc
86	Magnetico Inc.
87	Manugistics
88	Marotta Controls, Inc.
89	McCann Aerospace Machining Corporation
90	Meyer Tool Inc.
91	Micro-Coax, Inc
92	Microsemi Corporation
93	Mil Spec Sales Co.
94	Millitech, Inc
95	Morris Machining Co., Inc
96	MPC Products Corporation
97	Navigant Consulting, Inc
98	NMC Group, Inc
99	Norfil Manufacturing, Inc.
100	Northwest Composites Inc
101	NYF Corporation
102	O'Neil & Associates, Inc.
103	Onamac Industries, Inc.
104	Orion Industries
105	Paramount Machine Company, Inc
106	Parkway Products, Inc.
107	Parlex Corporation
108	PC Guardian
109	Performance Software Corporation
110	Perillo Industries, Inc.
111	PGM of New England, LLC
112	Plymouth Extruded Shapes
113	Port Electronics Corporation
114	Precision Gear
115	Precision Machine & Manufacturing Co.
116	Precision Tube Bending
117	Primus International
118	Product Manufacturing Corporation
119	PTC
120	QC Graphics, Inc.
121	Quest (Quality Engineering & Software Technologies) PVT Ltd.
122	Radant Technologies, Inc.
123	Relli Technology Inc
124	REMEC Microwave, Inc.

ID	Aerospace Industries – SECOND CONTACT SESSION
125	Rockwell Scientific Company LLC
126	Rodelco Electronics Corporation
127	Safe Flight Instrument Corporation
128	Sargent
129	SAS Institute, Inc
130	SC Integration, LLC
131	SEAKR Engineering
132	Sechan Electronics, Inc.
133	Senior Aerospace
134	Renaissance Services
135	Service Steel Aerospace
136	Servotronics, Inc.
137	Shoreline Electronics
138	Sigma Metals, Inc
139	Space-Lok, Inc
140	Sparton Corporation
141	Spectra Lux Corporation
142	Spincraft
143	Spirit Electronics, Inc
144	Sunbelt Industrial Supply Co. Inc.
145	Sypris Electronics, LLC
146	Tedopres International, Inc.
147	Telephonics Corporation
148	Texas Composite, Inc.
149	Thayer Aerospace
150	Therm, Inc.
151	Thermal Solutions, Inc.
152	Thomas James International
153	TMX Aerospace
154	Triad Design Service, Inc.
155	TTI, Inc.
156	Tyco Printed Circuit Group L.P.
157	UFC Aerospace
158	UGS
159	Universal Aerospace Co. Inc.
160	Universal ID Systems, Division of Commerce Overseas Corporation.
161	Unlimited Innovations
162	Vaupell Industrial Plastics
163	Vishay
164	Vulcanium Metals Incorporated
165	Waer Systems, Inc.
166	Welding Metallurgy, Inc.
167	Wems Electronics
168	Windings, Inc.
169	Xerox Corporation

TABLE 8 - Aerospace Industries – Second Contact Session

EXPLOITABLE RESULT	DESCRIPTION	POSSIBLE MARKET APPLICATIONS	STAGE OF DEVELOPMENT	COLLABORATION SOUGHT OR OFFERED	COLLABORATOR DETAILS	OWNER & OTHER PARTNER(S) INVOLVED	CONTACT DETAILS
KN_01: MFS Managing SW D&D Capability [OUT_06]	*Knowledge on design and developing of modular software for multifunctional acoustic sensors management in C language.*	1. Safety and Security (2007); 2. Aeronautics (2008).	Embryonic product (potential consultancy service)	Marketing Agreement offering on individual basis [DAPP]	To be identified.	***DAPP***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
KN_02: C2 and GUI SW D&D Capability [OUT_07]	*Knowledge on capability to design and developing of modular software for Command and Control Unit management and GUI interface in C language and in Windows NT® environment to show track data of acoustic tracking systems.*	1. Safety and Security (2007); 2. Aeronautics (2008).	Embryonic product (potential consultancy service)	Marketing Agreement offering on individual basis [CRBSD]	To be identified.	***CRBSD***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
KN_03: Microphone Phased Array D&D Capability [OUT_08]	*Knowledge on design and developing of acoustic phased array with more than 500 microphones.*	1. Safety and Security (2007); 2. Aeronautics (2008).	Embryonic product (potential consultancy service)	Marketing Agreement offering on individual basis [GRAS]	To be identified.	***GRAS***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
KN_04: SMC D&D Capability [OUT_09]	*Knowledge on design and developing of customised VME Bus computers for the management of multifunctional acoustic sensors.*	1. Safety and Security (2007); 2. Aeronautics (2008).	Embryonic product (potential consultancy service)	Marketing Agreement offering on individual basis [HYTEC]	To be identified.	***HYTEC***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
KN_05: System Simulation SW D&D Capability [OUT_10]	*Knowledge on design and developing of simulations for complex acoustic tracking systems.*	1. Safety and Security (2007); 2. Aeronautics (2008).	Embryonic product (potential consultancy service)	Marketing Agreement offering on individual basis [UOR]	To be identified.	***UOR***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
IP_01: MFS Managing SW [OUT_01]	*A multifunctional [CSCI-SP, CSCI-DH and CSCI-SC] sensor managing software developed in C Language and conform to FAA-STD-026 standards. Software will be completely or partially portable on other tracking acoustical systems even if with different HW configuration*	1. Safety and Security (2007); 2. Aeronautics (2008).	Software Prototype at the end of STEP 1 (without field testing validation).	Marketing Agreement offering on individual basis [DAPP]	To be identified.	***DAPP***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
IP_02: C2 and GUI SW [OUT_02]	*The Software will be completely or partially portable on other tracking acoustical systems even if with different HW configuration:* *- Command & Control management*	1. Safety and Security (2007); 2. Aeronautics (2008).	Software Prototype at the end of STEP 1 (without field testing validation).	Marketing Agreement offering on individual basis	To be identified.	***CRBSD***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*

EXPLOITABLE RESULT	DESCRIPTION	POSSIBLE MARKET APPLICATIONS	STAGE OF DEVELOPMENT	COLLABORATION SOUGHT OR OFFERED	COLLABORATOR DETAILS	OWNER & OTHER PARTNER(S) INVOLVED	CONTACT DETAILS
	software [CSCI-C2] developed in C Language and conform to FAA-STD-026 standards; *- User graphics interface software [CSCI-GUI] based on Windows NT® operative system to get track data visualization on two monitors. Acquired tracks are shown on the first monitor, while the second monitor is used to perform system queries starting from a table representation of track data. The second monitor is used also to signal collision risk situations and whether environmental noise, measured during search and tracking activities, exceeded noise limits.*			[CRBSD]			
IP_03: Prototype of Microphone Phased Array [OUT_03]	*One high directivity planar microphone phased array*	1. Safety and Security (2007); 2. Aeronautics (2008).	Hardware prototype at the end of STEP 1 (without field testing validation).	Marketing Agreement offering on individual basis [GRAS]	To be identified.	***GRAS***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
IP_04: SMC Prototype [OUT_04]	*Computer customized to manage a multifunctional acoustic sensor, build with VME Bus solutions. Electromagnetic shielding solutions will be in conformity with avionic needs. The Computer can be used, changing some customisations, for different multifunctional sensors.*	1. Safety and Security (2007); 2. Aeronautics (2008).	Hardware prototype at the end of STEP 1 (without field testing validation).	Marketing Agreement offering on individual basis [HYTEC]	To be identified.	***HYTEC***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*
IP_05: System Simulation SW [OUT_05]	*System simulation software founded on a Montecarlo code random generator [CSCI-ASIM e CSCI-SCEN] developed in FORTRAN 77 in conformity with FAA-STD-026 standards. The software can be used integrally or partially for numerical simulations of other tracking systems with some adaptations*	1. Safety and Security (2007); 2. Aeronautics (2008).	Software prototype at the end of STEP 1 (without field testing validation).	Marketing Agreement offering on individual basis [UOR]	To be identified.	***UOR***	*SECTION 3(Italian Airports, European Airports and Industries of TABLE 7 and TABLE 8)*

TABLE 9 – Publishable Results- Description

3 ANNEX II – PUBLISHED SCIENTIFIC PAPERS

Acoustic System for Aircraft Detection and Tracking based on Passive Microphones Arrays

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San Diego, November 2004

Abstract

The present study is conducted within a project included in the Sixth Framework Program of the European Union. The project, whose acronym is SAFE-AIRPORT, involves the development of an acoustic system based on two Passive Phased Array Microphone antennas, which are to be located in open environments, and capable of detecting and tracking airplanes at a distance in air and on ground.
Each antenna array is made up of a series of microphones arranged on a rotating planar support. Array's spatial selectivity is discussed aiming to optimize beam-forming design according to spectral properties of common jet aircrafts. In particular, the influence of the number and the geometric distribution of microphones is shown in function of the target's acoustic frequency and signal to noise ratio sensitivity.
The system's range is estimated at different working frequencies and for different positions of the aircraft on the horizon. The effect of wind gradients on the estimation of the aircraft position is also modeled and computer simulations showing consequent deviation of acoustic waves are performed.
Finally, possible developments in antenna design, such as the use of three fixed planar-arrays in tetrahedral configuration instead of one rotating planar-array, are evaluated showing expected advantages.

1. Introduction

The present research is conducted within the Sixth Framework Program of the European Union in the project named SAFE-AIRPORT, which involves the development of an innovative acoustic system based on two Passive Phased Array Microphone antennas capable to detecting and tracking airplanes up to a considerable distance in air and on ground. The system is integrable with airports air traffic management procedures and it is a possible effective air control system for ATZ (Aerodrome Traffic Zone); in particular, it is proposed to be autonomous for smaller airports and integrated with standard control systems for larger airports. The system consists of two acoustic arrays (see figure 1), to be used in open environments, and a control unit linked to each sensor through fibre optics connection, with a control console, managed by an operator, to be installed inside the airport structure. The main advantages of SAFE-AIRPORT system, in comparison with conventional radar systems, will be the lower cost, and it will be electromagnetic and pollution free. Moreover, it is an approach to a redundant design philosophy.

The sensors consist of a plane 2-D phased array of microphones, a dome and control computer that will allow the sensors to perform the planning and the execution of detection and tracking activities in a prefixed search volume, in complete autonomy.

The standard configuration is: the microphones lie on a rotating antenna array plane having a constant slope of 30° respect to the floor. The antenna plane contains a 2-D microphone array.

The listening beam is electronically steered towards the selected search angular quantum (Search Task) or towards the tracking direction. This is obtained using an array of phase shifters put in one to one correspondeance with the microphones. The computer controls the phase shifters array to obtain the beam focusing and the beam steering, in order to guarantee the shape and direction of the listening beam.

The Control and Command Unit consists of a computer with two monitors, which is linked to the sensors through an optical fibre Ethernet connection.

The technique adopted for tracking the aircrafts with two sensors of 512 microphones is the beam-forming that allows to recognize a weak acoustic target by steering the total beam of the microphones' array in the target direction.

2. Beam-forming

An antenna able to perform electronic scanning, called Phased Array, is well known and is made of many elements assumed to have identical features and lying on a plane. They are fed with a signal that is amplitude-and-phase-controlled. Be called r_i the position of each microphone in a tri-dimensional coordinate system and u the unit-vector corresponding to the direction of the arriving acoustic plane wave, then the radiation diagram of the phased array is given by the product of the radiation diagram of the single microphone and the array factor: $e^{jkr_i \bullet u}$ where j is the imaginary unit, k=2πf/c is the wave number and c is the speed of sound in the medium. In the present project, the microphones are located on a plane and when their output is added in phase, this generates a peaking of the beam pattern and shifting by a fixed phase-angle the output of the microphones before adding them is equivalent to steer the beam pattern in another direction. Moreover, the optimisation of the antenna depends on the temporal frequency of the signal to be received, which defines the minimum distance between the single microphones and the total size of the array.

For instance, it can be shown that if the distance between the single microphones is higher than λ/2 (λ the actual wavelength to the frequency of the plane wave) “grating” lobes occur. Grating lobes are additional unwanted beams that appear in the radiation diagram of the phased antenna array generating uncertainties in the angular resolution of the target. Figure 2 shows what happens when the inter-microphone distance is λ and the beam is not steered.

Furthermore, at a given frequency of the acoustic wave the angular spread of the main beam depends on the linear width of the antenna. In Figures 3 various arrays with different number of microphones (but with λ/2 as inter-microphone distance) are simulated and it is evident that the larger the size of the array (and the number of microphones, because the minimum inter-microphone distance is fixed to avoid grating lobes), the smaller is the width of the main lobe (and the better the angular discrimination capability of the antenna).

The above discussion is valid for ideal microphones (having all fixed and identical characteristics). However, real microphones cannot be thought as completely identical and some deviation in the amplitude and phase from the expected ones must be taken into account.

Figure 4, shows that if each microphone is affected by a considerable random amplitude noise (20%) due to different sensitivity of single microphones together with a random phase noise, due to different resonant frequency, uniformly distributed between ±15°, the beam of the whole array is slightly changed but practically unaffected. This is a consequence of the large number of microphones of the antenna array that largely compensate irregularities of the single microphones (random distributed).

3. Range evaluation resulting from antenna design and target properties

3.1. Working frequency of the antenna array

The antenna array detects the target by sensing the incoming acoustic waves in a fixed small frequency range. The array must be optimised for the detection frequency. Therefore, this frequency must be carefully selected and must match the acoustic spectral properties of the aircraft to be detected. Here is assumed to work with a single travelling frequency and not to apply convolution techniques for the present.

However, the spectral properties of the aircraft noise change considerably with the time and the position of the aircraft. Figure 5 represents only an example taken a few seconds after take-off for a MD80 aeroplane. However, it can be drawn, as general conclusion, that the energy is higher for low frequencies.

In this paper, two specific temporal working frequencies will be considered. The two frequencies that will be taken into account are 2500 Hz and 1000 Hz. As known, an higher frequency makes possible to design an array of smaller linear width at a fixed beam width; for instance, taking the simpler case of one-dimensional arrays, the beam width is: $\pm 2 \sin^{-1} (c/f\,L)$ [1]; where c is the speed of sound in the medium, f is the frequency of the acoustic wave and L is the total linear length of the array. For this reason 2500Hz should be preferred. However, as it will be shown later, the range of the system is considerably higher at 1000Hz.

3.2. Range evaluation

The larger is the antenna, at a fixed inter-microphone distance ($\lambda/2$), the better is its angular discrimination capability. In order to determine the size of the antenna, the required directivity of the phased array must be decided. In the following calculation, it will be assumed an antenna directivity of about 32 dB corresponding to a solid angle of 0.008sr (about 5° in elevation and azimuth) [3]. Figure 6 shows that, to achieve such directivity with a phased array of omni-directional microphones, about 500 sensors are required and a circular antenna with a diameter of about 2 meters at 2500Hz.

In the following, the range of the system will be calculated assuming a source acoustic power level of 140 dB in all directions and in the frequency range up to 3 KHz (reasonable value for a jet aircraft) and a background noise level of 55 dB (linear scale). Considering that we would try to discriminate the target at the working frequency of 2500 Hz, we will filter the noise around this value (for example, filtering to 1/3 octave); after filtering, the noise power density level is about 39dB. To achieve a signal to noise ratio of 10 dB, the aircraft power density level at the antenna must be, after attenuation, at least 49 dB. A simple equation will give the intensity power level at the antenna in function of the range for omni-directional noise sources:

$$J_R = \frac{Sourcepower}{4\pi R^2}\frac{1}{L_0}\frac{1}{L_M}\frac{1}{L_A}$$

The attenuation factors considered in the calculation are: the maximum loss due to aircraft orientation (L_0 =3dB); the meteo factor (L_M) which, in case of heavy meteorological conditions is about 7 dB; the air attenuation (L_A), which depends on the range and is about 0.01 dB/m at 2500 Hz (for values of the relative humidity between 40% and 60%) and 0.005 dB/m at 1000 Hz [2] [4]. Moreover we must consider the spherical divergence loss typical of waves generated by punctual acoustic sources; as known, this loss depends on the square power of the range.

After taking into account all these losses and the required minimum signal to noise ratio, it turns out that the maximum range is about 3Km at 2500Hz. However, when the beam is not pointing at the horizon, the noise is sensed by the antenna only through the side lobes (of about 20 dB lower level than the main beam). Consequently, the maximum range increases by 70%, also up to about 5Km.

In order to improve the range, a lower working frequency can be chosen to reduce the attenuation losses due to the medium. For example, given a frequency of 1000 Hz, the air attenuation is about the half at the same distance. However, unless we don’t increase the size of the array, the directivity of the antenna diminishes because the main beam becomes wider.

Taking into account both effects (reduced attenuation of the medium and reduced directivity of the antenna array) and leaving unchanged the antenna diameter, a maximum range of about 5Km at 1000Hz can be reached when the beam is pointing at the horizon and a maximum range of about 8Km can be reached when the airport background noise is sensed by the antenna only through the side-lobes (for example, when the aircraft is almost vertical above the antenna).

However, a disadvantage of working at a lower frequency is that, as previously said, given a fixed size of the array, the main beam is wider and, consequently, the position uncertainty in the detection of the aircraft is larger.

4. Effect of the Wind and air temperature gradients

The antenna array, is able to recognize the direction of the acoustic wave coming from the aircraft. Two antennas, opportunely located, are able to triangulate their information and compute, in this way, also position and distance of the target. However there is an element that we have not yet considered until now, that is: the effect of the wind and temperature gradients. Wind gradients modify the propagation direction of the wave. In first approximation the horizontal gradients of the wind will be neglected because it will be assumed that this component of the gradient is of moderate intensity. However, the vertical gradient of the wind cannot be neglected because, as known from the physics of atmosphere, this gradient can be strong in the first hundreds meters of height. According to the meteorology sciences, the value of the wind velocity can be roughly computed as $k\,(v_0)^h$ [5], where k is a constant, v_0 is the velocity of the wind measured near the ground, and h is the height. Subject to a correct estimation of the involved constants, the vertical gradient of the wind can be easily deduced by this equation and, given the wind speed, the modification of the acoustic wave trajectory follows from the integration of this equation:

$$tg(d\vartheta) = \frac{\partial v}{\partial b} d\tau = \frac{\partial v}{\partial z} \sin(\vartheta) \frac{dl}{c+v} = \frac{\partial v}{\partial z} \frac{dx}{c+v}$$

where dθ is the deviation of angle (due to wind gradient) of the propagation direction of the wave, b is the unit vector parallel to the plane of the propagating plane wave, v is the local wind velocity, dτ is the time that the wave needs to propagate along a path of length dl (dx=dl sin(θ) if dx is the projection of the propagation path on the horizontal plane). This equation can be derived with the help of geometric arguments (see fig. 7) in the hypothesis that the gradient of the wind is different from zero only in vertical direction (z axis).

It follows from the above equation, given that the gradient of the wind is supposed different from zero, only in vertical direction, that the propagation trajectory of the acoustic wave lies completely in one plane. This means that, in the hypothesis above, only the elevation angle of the coming wave is affected by the wind gradient while the wind has no influence on the estimation of the azimuth angle.

Figure 8 shows the deviation from the straight trajectory for different values of the wind on the ground.

5. New Developments and Open Issues

In the present design, the antenna arrays are mounted on rotating joints. This is similar to the electromagnetic approach (airport radars). However, in the acoustic version, this approach has two main drawbacks: even using a rotating motor very moderately noisy there is the cinematic noise induced on the microphones (moving in air with a "local wind" effect and related added noise) by the rotation of the sensor and Doppler effect due to the motion of the sensor and affecting the received spectrum of the signal to be detected.

The impact of both effects on the performance must be evaluated and the task is complicated by the circumstance that both the noise due to the local wind created by the rotation and the Doppler effect depend on the position of the individual microphones on the plane of the array. In first approximation, the cinematic noise generated on the microphones can be considered uncorrelated and, for this reason, one could deduce that, being the useful signal on all microphones correlated, by increasing the number of microphones of the sensor, the impact of this noise on the final performance can be minimised. In fact, be k the useful correlated rms amplitude signal of each microphone and α_i the cinematic noise contribution of the i-esim microphone; the signal-to-noise with n microphones is: $\frac{S}{N} = \frac{n^2 k^2}{\sum_{i=1}^{n} \alpha_i^2}$ and improves increasing the number of microphones n. However the cinematic noise contribution α of each microphone depends on its distance from the center of the rotating array. Therefore, the increase in the number of microphone cannot be pursued enlarging the array (the microphones in the periphery of the array would be more affected by wind due to rotation) but increasing the density of microphones, especially in areas of the array plane near the center where the rotational velocity of the microphones is low and so low the induced cinematic noise.

The Doppler shift is not the same on every individual microphone and is periodically changing with the rotation of the antenna. Therefore, the noise components that add after the multiplexer correspond, for each microphone, to a slight different frequency from the desired one. The maximum amount of the shift for typical rotational velocities of the antenna (1s to 4s for rotation) is moderate but a deterioration of the performance of the system cannot be excluded and tests on the field must be performed.

However both drawbacks could be eliminated by an innovative design of each sensor. Instead of having a single rotating plane array, three arrays pyramidally disposed could be foreseen, each spanning 120° without the need to rotate. In this way, the number of microphones equipping the antenna is multiplied but the rotating motor is eliminated and both cinematic noise and Doppler effect due to the rotation disappear.

Furthermore, another solution could be envisaged to reduce the number of microphones on each array without impairing the directivity and performance of the antenna. For instance, in one design, the disposition of the microphones could be cross-shaped. In this way, the number of microphones with respect to a rectangular or circular array of comparable diameter would be drastically reduced. However, all possible implications of this technical choice must be accurately examined.

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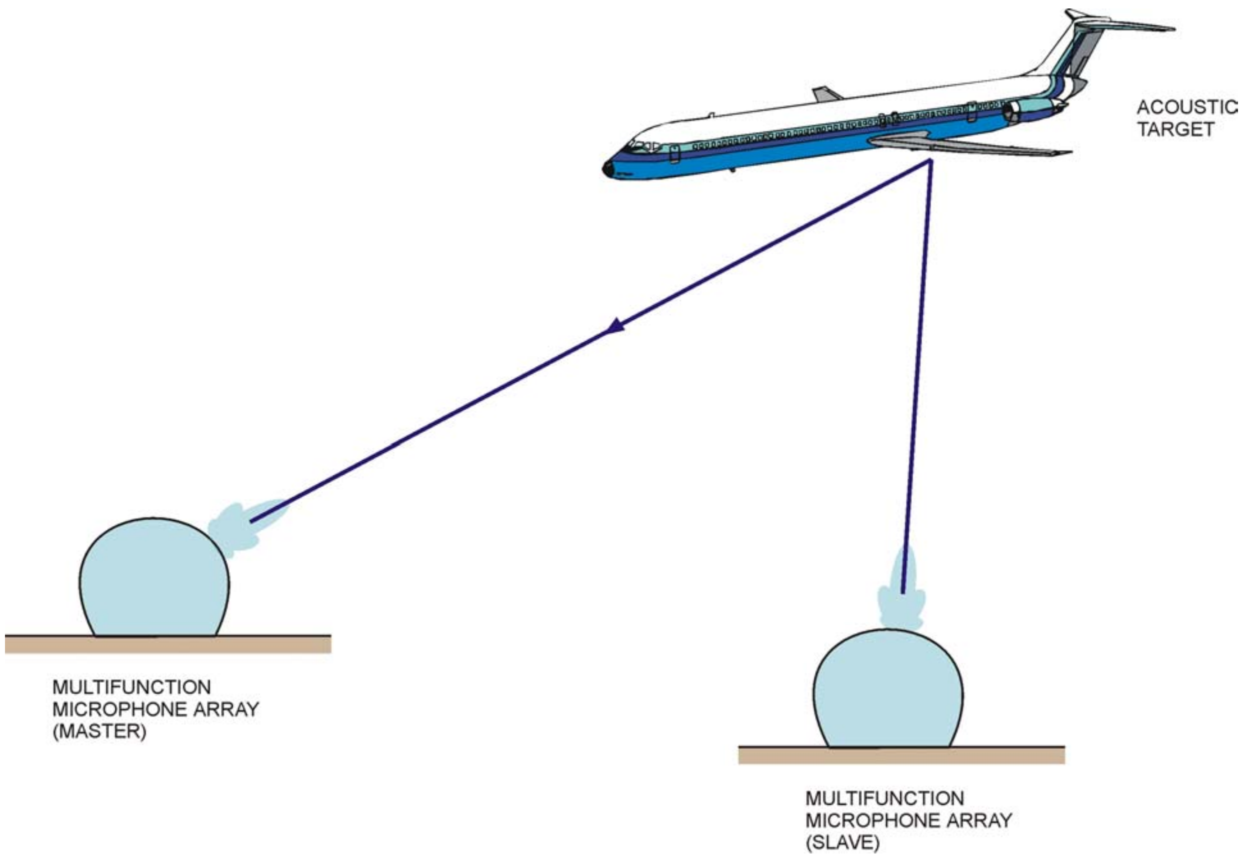

Figure 1: ***SAFE-AIRPORT*** **System - Employment Scheme**

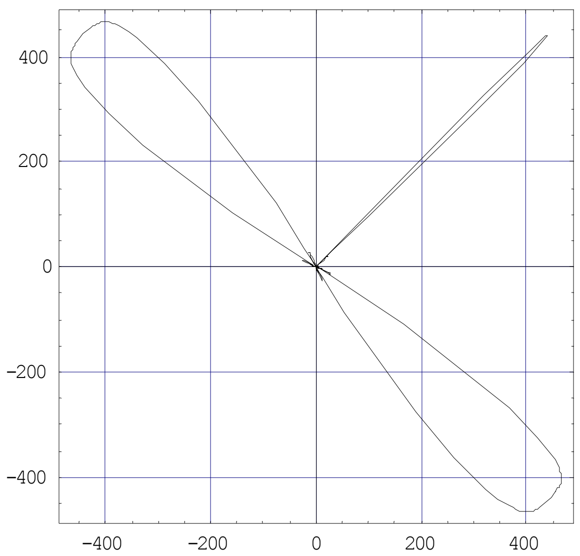

Figure 2: Diagram obtained with the package Mathematica®; Directional sensitivity of a linear array with 25 microphones at distance λ=14cm (source frequency = 2.5 KHz). When the beam is not steered, λ is the minimum distance between the microphones in order to avoid grating lobes. Polar plot.

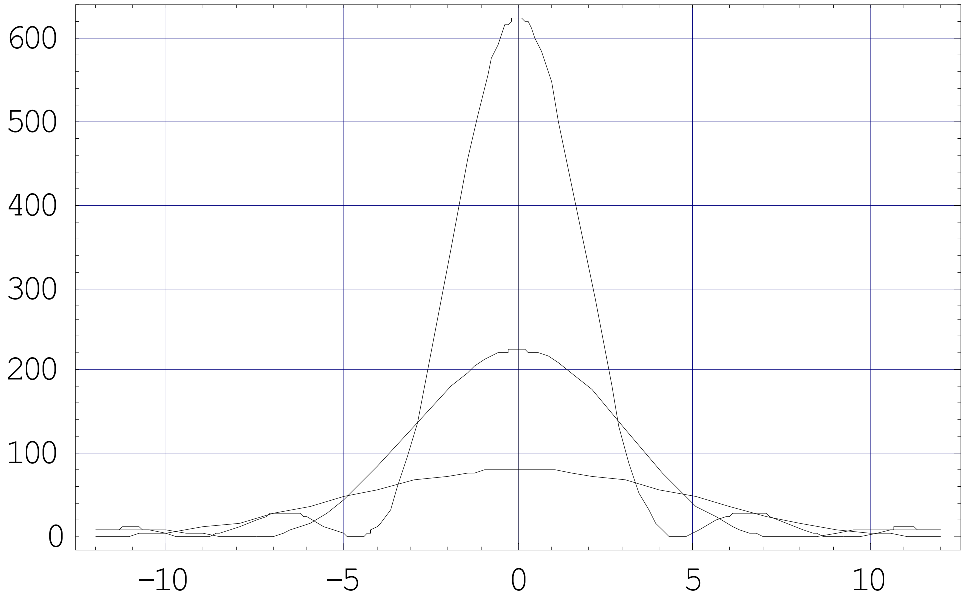

Figure 3: Diagram obtained with the package Mathematica®; Directional sensitivity of a linear array with respectively 9, 15 and 25 microphones at distance λ/2=7cm (source frequency = 2.5 KHz). Angles in degrees are represented on the x axis in the range ±12 degrees and the relative amplitude is represented on the y axis with linear scale.

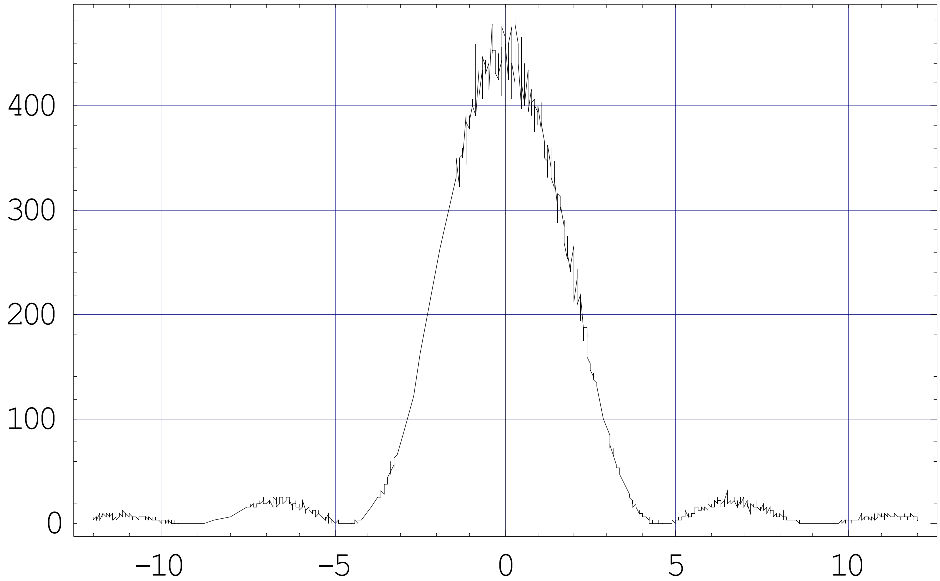

Figure 4: Diagram obtained with the package Mathematica®; Directional sensitivity of a linear array with 25 microphones at distance λ/2=7cm (source frequency = 2.5 KHz). The total length is 2.12 m. Random noise is simulated (random phase noise on every microphone uniformly and independently distributed over ±15 degrees and amplitude random noise of maximum 20%). Angles in degrees are represented on the x axis in the range ±18 degrees and the relative amplitude is represented on the y axis with linear scale.

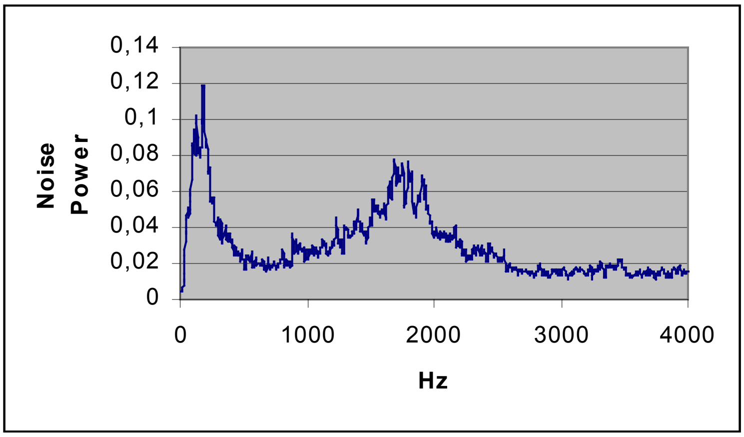

Figure 5: Noise Spectral Power of a MD80 during takeoff in linear scale

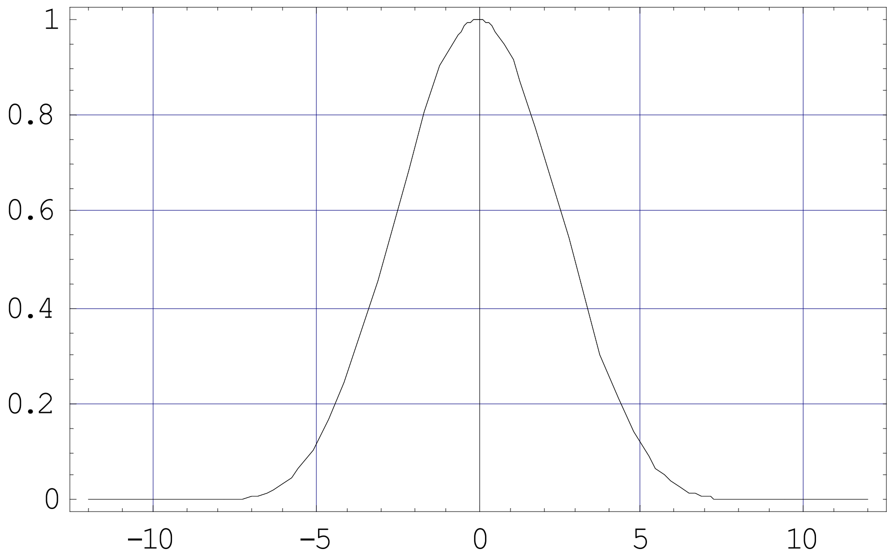

Figure 6: Diagram obtained with the package Mathematica®; Directional sensitivity (section of the beam) of a circular array with 490 microphones at distance $\lambda/2$=7cm (source frequency = 2.5 KHz). Angles in degrees are represented on the x axis in the range ±12 degrees and the relative amplitude is represented on the y axis with linear scale.

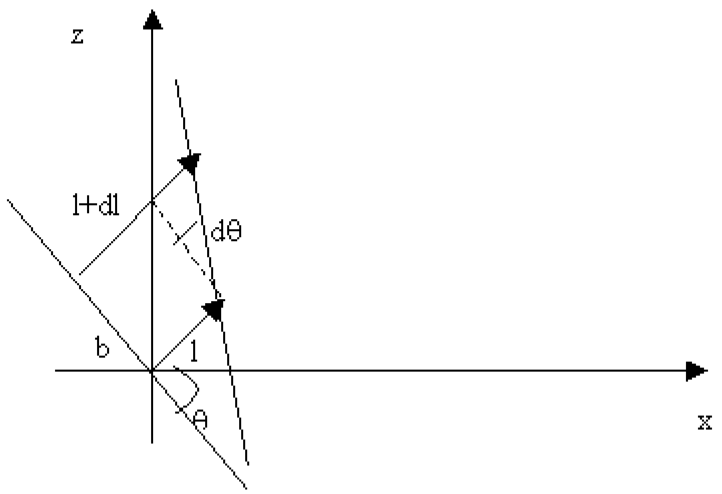

Figure 7 : Graphic representation of the angle deviation (dθ) during a path dl of the acoustic plane wave due to vertical wind gradient.

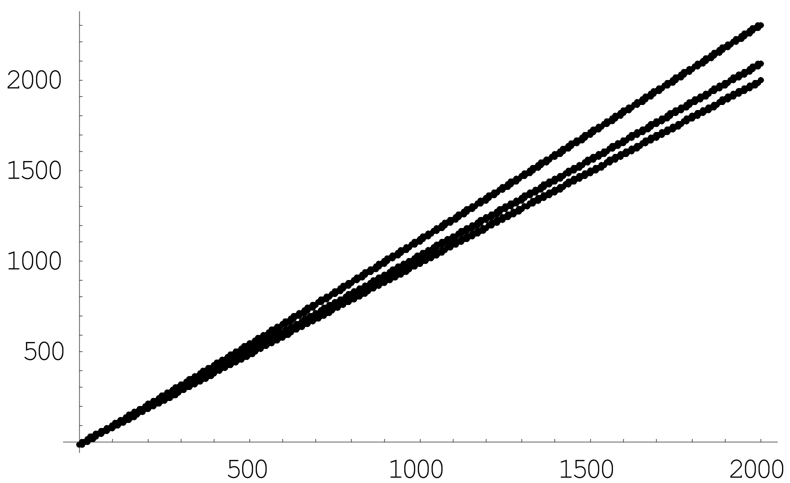

Figure 8: Trajectory of the acoustic signal coming from the aircraft and directed to the antenna array for various speeds of the wind on the ground. (0m/s, 2m/s, and 7m/s). The wind is assumed oriented parallel to the ground (meter is the unit on both the horizontal and vertical axis).

Outdoor Sound Propagation Effects on Aircraft Detection through Passive Phased Array Acoustic Antennas: 3D Numerical Simulations

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150th ASA MEEETING/NOISE-CON 2005
MINNEAPOLIS, MINNESOTA
17--21 OCTOBER 2005

Abstract

The present paper describes some of the main acoustic issues connected with the SAFE-AIRPORT European Project for the development of an innovative acoustic system for the improvement of air traffic management. The system sensors are two rotating passive phased array antennas with 512 microphones each. In particular, this study focused on the propagation of sound waves in the atmosphere and its influence on the system detection efficiency.
The effects of air temperature and wind gradients on aircraft tracking were analyzed. Algorithms were implemented to correct output data errors on aircraft location due to acoustic rays' deviation in 3D environment. Numerical simulations were performed using several temperature and wind profiles according to common and critical meteorological conditions.
Aircraft location was predicted through 3D acoustic rays' triangulation methods taking into account variation in speed of sound waves along rays' path toward each antenna.
The system range was also assessed considering aircraft noise spectral emission. Since the speed of common airplanes is not negligible respect to sound speed during typical airport operations such as takeoff and approaching, the influence of the Doppler Effect on range calculation was also considered and most critical scenarios were simulated.

1. Introduction

The physical state of the atmosphere strongly affects outdoor sound propagation both in terms of acoustic rays deviation (geometric effects) and of sound energy attenuation (intensity effects) [1] [2]. In particular, atmospheric refraction has the strongest and most variable influence on noise propagation.

Refraction is caused by changes in sound speed vector along the acoustic propagation path in the atmosphere, which are mainly due to air temperature and wind gradients.

This phenomenon determines a deviation of acoustic rays which must be taken into account in order to correct SAFE-AIRPORT raw output data on aircraft location [3]. In fact, this 3D detection system is based on the triangulation of output sound rays data from two rotating passive phased array antennas. Each antenna senses the sound waves incident direction, which provides the aircraft position only in case of linear acoustic rays, that is, in case of no changes in sound speed vector. On the contrary, in real meteorological conditions air temperature and wind speed profiles are needed to predict real acoustical wave paths from source to receiver. Consequently, a 3D model was implemented with air temperature and wind profiles as input data and returning the refraction-corrected aircraft position as output data.

The model provides also an estimation of the system limits in terms of range calculation and of estimation of acoustic shadow zones.

Besides the loss of sound energy density due to 3D geometrical spreading, other effects such as atmospheric absorption and scattering of sound energy are important to predict the antennas range which depends on the received sound level. These processes act in combination as the acoustical waves propagate through the air from a source to a receiver. They lead to an excess attenuation with respect to free field propagation, which is a function of the sound frequency. Given the high antennas directivity (narrow beam), the effects of reflections by objects on ground and of environmental background noise on the received sound level were neglected. Instead, Doppler effect is relevant due to the fact that the speed of common airplanes during typical airport operations is not negligible respect to sound speed.

2. 3D model for air temperature and wind gradients effects

As the SAFE-AIRPORT system is meant to investigate within the ATZ (Aerodrome Traffic Zone), which typically extends from the surface to an altitude of 1000-2000 ft (300-600 m) above aerodrome level (aal), then the portion of atmosphere to be considered in the model is the atmospheric boundary layer (ABL). In fact, the ABL is the ground-based layer of the atmosphere and typically reaches up to 1000 m in height or more. It is characterized by the vertical exchange of momentum, energy (heat) and mass (water) between atmosphere and ground [4].

Atmospheric motions within the ABL cover a broad variety of time and length scales. The state of the atmosphere on the scales greater than that of typical noise problems (macroscale and mesoscale) is a deterministic parameter for the propagation of sound. Small scale (microscale) atmospheric motions (turbulence) act in a more statistical sense.

The meteorological condition for a specific noise event is first of all given by the macroscale weather situation, i.e. the position of cyclones and anti-cyclones relative to a site of interest. These conditions, the time of day and the local land determine the acoustically relevant gradients to a large extend. However, in complex the macroscale meteorological field is often superimposed by topographically induced mesoscale circulation systems. The mesoscale wind speed can be of the same order of magnitude as the macroscale wind speed such that the local wind direction is completely changed by mesoscale systems [5]. Many mesoscale systems are thermally driven and change their direction according to the time of the day. Prominent systems of this kind are land-sea breezes (day: low-level flow from sea to land; night: low-level flow from land to sea), valley-mountain winds (afternoon: valley up; morning: valley down), and slope winds (day: upslope; night: downslope).

Under some conditions (simple topography, thermal homogeneity of earth surface, no high buildings or structures and considering relatively microscale areas) then the atmospheric parameters depend only on height (horizontal homogeneity hypothesis). Those conditions are substantially satisfied within common ATZs, as airports are generally located in plains with no particular thermal heterogeneities and in scarcely inhabited areas. Therefore, the atmosphere was modeled as a series of horizontal layers within which air temperature and wind speed are uniform. Layers thickness Δz can be customized according to input profiles vertical accuracy.

As regarding the time-scale, wind cannot be assumed as stationary, as high frequency turbulence (cycle time < 1s) prevail in the ABL. Consequently, almost real-time measurements are needed to update the model input data.

However, wind always increases with altitude, except for particular conditions in the second half of clear-sky nights (Lower-Level Jet effect or LLJ). In fact, as usual in boundary-layer flows, the fluid speed (i.e. wind in this case) is null on the solid surface (i.e. on ground) and increases with distance from the surface asymptotically to the undisturbed fluid speed (i.e. the geostrophic wind).

Temperature profiles are quite more complex. Neutral stratification occurs in case of high cloud cover or strong winds with temperature gradient $dT/dz = -10$ °K/km. During daytime and little cloud cover the atmosphere is heated from the ground and the vertical temperature stratification becomes super-adiabatic and unstable ($dT/dz < -10$ °K/km). Opposite to this, the air is cooled during cloudless nights. In this case an inversion layer forms near the surface in which the temperature rises with height and the stratification is stable.

As well known the refraction of sound waves can be calculated through the Snell's law which can be expressed by the following equation [6]:

$$\frac{\cos\theta}{V} = \mathrm{cost} \qquad 1)$$

where θ is the elevation angle and V is the effective sound wave propagation speed. Given the great distance from the antennas, an airplane can be considered as a point source and the acoustic waves are considered as planar with good approximation. Taking into account the profiles of wind speed components v_x, v_y, v_z (in m/s) and of temperature t (°C), then the Snell's law becomes as follows (Figure 1):

$$\frac{\cos\theta}{c(t)+v_x \sin\varphi\cos\theta+v_y \cos\varphi\cos\theta+v_z \sin\theta}=\cos t \qquad 2)$$

where φ is the azimuth angle and c is the speed of sound in still air, which depends on t according to the following expression [7]:

$$c=\sqrt{\gamma\frac{p_o}{\rho_o}}\cdot\sqrt{1+\alpha\cdot t} \qquad 3)$$

where γ is the adiabate exponent of air, which is equal to $1.402 = c_p/c_v$ (ratio of the specific warmth respectively at constant pressure and volume), p_o is the atmospheric air pressure, ρ_o is the density of air, α is the expansion coefficient. All parameters in equation 3 are referred to the temperature of 0 °C.

When the calculated elevation is zero then total reflection occurs and the new elevation value is set to the additive inverse $-\theta$ of the value in the previous computational step.

Starting from the raw output data (received sound ray direction at each antenna) the acoustic wave path is reconstructed within the ATZ (ray tracing procedure). Aircraft position is determined by triangulation of deviated acoustic rays from two antennas. As the two rays may not encounter in a determined point the model finds the central point of the minimum distance segment between the two rays.

3. Time delay data correction

Another important aspect to be considered is the propagation time delay of acoustic signals. Since the speed of sound is relatively slow (in comparison with the speed of light for conventional radars), then acoustic sensors receive the signal emitted by a source entering the ATZ after several seconds.

Moreover, the same source is sensed by each antenna at a sensibly different time depending on each antenna-source distance and on sound speed variations along each acoustic ray. For this reason the 3D aircraft position must be reconstructed a posteriori through time-delay correction.

Typical TDE (Time Delay Estimation) algorithms proposed by several authors are based on the application of convolution and cross-correlation functions of different sensors output having in input the emitted signal and the sensors channel response [8][9][10].

When emitted signal is unknown, but transmission paths and sound speed can be obtained, then simple iterative algorithms can be used. A proposed methodology can be pointed out on the following basic procedure.

Be the two antennas named respectively M and S and be the aircraft position identified by P. When the aircraft is flying within the system range its noise waves are sensed by each antenna. From that time on each antenna provides a time series of signals.

Initially, the two signals received by M and S at a same given time τ_0 are used for triangulation and a virtual aircraft position P_0 is calculated. Successively, the sound wave transmission paths from P_0 to M and from P_0 to S are determined and reception time-delay $\Delta\tau_{MS,0}$ between the two antennas is calculated. In the next iteration step the triangulation procedure is performed considering the signal received by S at the time $\tau_1 = \tau_0 + \Delta\tau_{MS,0}$ and a new aircraft position P_1 is found (Figure 2).

The iterative process goes on unless $\Delta\tau_{MS,n} = 0$ (convergence condition) after n iterations. The correspondent point P_n is assumed as the real aircraft position P at the time $\tau = \tau_0 - \tau_{PM}$, where τ_{PM} is the propagation time delay from P to M, which is computed as $\tau_{PM} = \Sigma_i(\Delta s_i/V_i)$, where i is the generic atmosphere layer from P to M, Δs_i is the sound wave propagation path within layer i and V_i is the effective sound speed in the same layer. The next aircraft position in the track can be determined by repeating the iterative procedure starting from the signal received by M and S at the following time step, i.e. respectively at the time (τ_0 + dτ) and (τ_0 + Σ_j $\Delta\tau_{MS,j}$ + dτ), where j is the generic iteration from 1 to n in the previous position correction.

Refinement and improvement of time-delay correction algorithms are under study in order to reduce computation time taking into account hardware capabilities optimization according to processors power and architecture.

4. System acoustical limits and test scenarios

The system range mainly depends on the antennas characteristics, on the meteorological conditions (atmospheric acoustic absorption) and on the aircraft sound emission (sound level and spectrum).

The aircraft can be well approximated as an omni-directional point source radiating in free space. Therefore, the range was estimated through the following formula [11]:

$$N + SNR - G_m = L_0 - 20\log\left(\frac{r}{r_0}\right) - A \qquad 4)$$

where N is the background noise, SNR is the minimum Signal-to-Noise Ratio required to distinguish the source presence from the background noise, G_m is the antenna gain with m microphones, L_o is the aircraft noise level at the distance r_o, r is the source-antenna distance and A is the excess attenuation. N, G_m, and L_o in equation 4 are expressed in dB ref. 20 µPa and distances are in m.

In the first member of equation 4 receivers technical characteristics are represented. The final system will be provided with two 512-microphone planar antennas (G_m = 54 dB), which are designed through appropriate beam forming techniques to achieve high directivity. In Figure 3 the simulated narrow beam of a 25-microphone linear array is shown for different spectra of the received signal. The use of very narrow beam (pencil beam) antennas improves detection accuracy and make ground effect and environmental background noise practically negligible. Consequently, N is due only to the microphones inherent noise floor, also called inherent thermal noise (N = 27 dB with low-noise level microphones).

The excess attenuation in the present model is due only to atmospheric absorption and can be expressed as $A = \alpha\, r$, where α is the acoustic absorption coefficient, which can be calculated by the following equations, according to international standards [12] [13]:

$$\alpha = 8.69 \times f^2 \left\{ 1.84\times10^{-11}\left(\frac{T}{T_0}\right)^{1/2} + \left(\frac{T}{T_0}\right)^{-5/2}\left[0.01275\frac{e^{-2239.1/T}}{F_{r,O} + f^2/F_{r,O}} + 0.1068\frac{e^{-3352/T}}{F_{r,N} + f^2/F_{r,N}}\right]\right\} \qquad 5)$$

where f is the sound frequency, $F_{r,0}$ and $F_{r,N}$ are respectively the oxygen and the nitrogen frequency relaxation factors (in Hz) given by:

$$F_{r,O} = 24 + 4.04\times10^4 u \frac{0.02+u}{0.391+u} \qquad 6)$$

$$F_{r,N} = \left(\frac{T}{T_0}\right)^{-1/2}\left(9 + 280 u e^{\left[-4.17\left(\frac{T}{T_0}\right)^{-1/3} - 1\right]}\right) \qquad 7)$$

where u (%) is the molar concentration of water vapor (which can be obtained by the relative humidity η (%) as $u = 0.02337\eta$), T_0 = 293.15 °K = 20 °C and T is the temperature in °K.

The noise curves available from the FAA-INM 6.1 aircraft database were used in the simulations [14] [15], while emitted spectra were obtained from digital audio processing (DFT and smoothing algorithms) of in-situ measured data. Also signal filtering at 20, 10, 5 and 2.5 kHz was simulated in order to analyze the system performance after high-frequency cutting.

Another system limit is due to acoustical shadow zones, which are generated in the case of upward refraction. Into such zones sound energy is not directly shed from the aircraft so that the source location can not be performed. The worst scenario is given by super-adiabatic and unstable atmosphere with the maximum temperature decrease with height and upwind propagation.

5. Simulations and results discussion

The system range was assessed by evaluating antenna *SNR* at ATZ border, which was simulated at a radius of 2.5 NM (4630 m) and centered in the antenna.

It is interesting to notice from equations 5 to 7 that the dependence of α with T and η is very complex and it is not immediate to individuate the most critical meteorological conditions for range estimation. Simulations showed that the poorest *SNR* values are obtained in case of very low humidity (η = 10%) at about t = 5-15 °C depending on the aircraft model (Figure 4).

As regarding the acoustic source, small airplanes generally resulted less difficult to detect than big jet aircraft, but the emitted noise spectrum also had a relevant influence on atmospheric attenuation (Figure 5). Moreover, it is important to take into account the spectrum shift (Doppler effect) due to the aircraft speed component v with respect to the antennas:

$$f_D = f\left(\frac{V}{V - \mathrm{v}}\right) \qquad 8)$$

where f_D is the frequency shifted for the Doppler effect and v > 0 when the airplane is moving toward the antenna. Approach resulted to be the most critical airport operation, because the airplane engine-power is at its minimum thrust and noise level (Figure 6 and 7) and at the same time, the Doppler effect causes a relevant spectrum shift to the higher frequencies, which are the most affected by air absorption (Figure 8). For the same reason, high-frequency filtering revealed to provide effective advantage on system range. In particular, major *SNR* improvement was obtained with f < 2.5 kHz for most jet aircraft models (Figures 9).

3D simulations of aircraft refraction-corrected position gave sensible results in all tested meteorological scenarios, including hard model conditions such as temperature inversion and total reflection. Output data are provided as numerical results (Table 1) and 3D graphs or animations along with the input profiles (Figures 10 and 11). Air temperature and wind gradients induced an important error on aircraft position, which usually increased with the distance from the antenna, reaching up to several hundreds of meters in some meteorological conditions.

Assessment of acoustic shadow zones was also carried out through 3D simulations in function of input atmospheric profiles (Figure 12). Results were visualized through horizontal and vertical plane sections for a more detailed study with respect to common aircraft trajectories within the ATZ (Figure 13). In the worst scenarios shadowed zones were strongly anisotropic as shown in Figure 13, indicating that wind direction plays a greater role than temperature gradients which would induce a radial symmetry.

6. Conclusions

Though experimental data will be needed for model validation, the present simulations provided interesting general indications. However, data from on-field testing are being currently collected and will be used even as a guide for further model refinements.

In particular, the simulations showed that refraction-induced error on aircraft position can not be neglected within the ATZ in most common meteorological scenarios. Besides, the system range resulted to be strongly dependent on sources spectra and atmospheric conditions. In any case, high-frequency cutting filters at 5 kHz, or even less, are necessary for reasonable range performance (SNR > 10 dB within ATZ of 2.5 NM radius) for common aircraft models.

Most importantly, acoustic shadows must be considered, especially when antennas are receiving downwind. Since shadow zones depend only on atmospheric conditions and source-receiver geometry, antennas location must be accurately studied with respect to local winds properties.

In future studies, the role of wind turbulence on detection accuracy will be investigated. Moreover, research activity will also be conducted on the implementation of aircraft recognition algorithms through acoustic spectral analysis. On this subject, comparison between conventional techniques and experimental application of neural networks will be explored.

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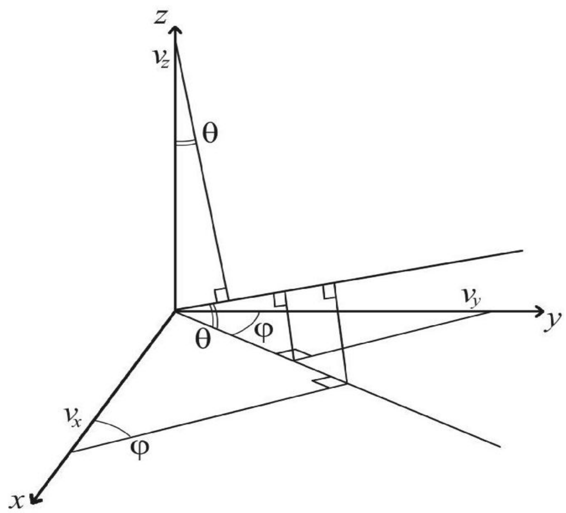

Figure 1. Wind speed components v_x, v_y and v_z in the Cartesian reference system xyz and wind direction in terms of azimuth φ and elevation θ.

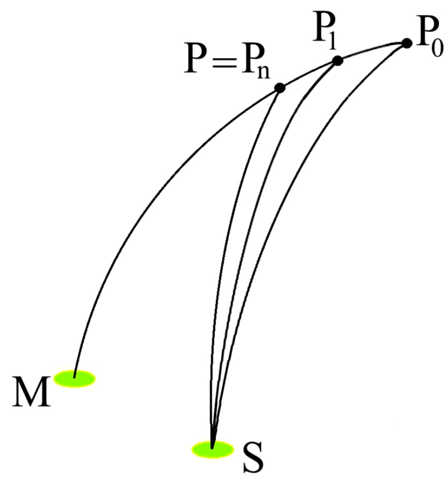

Figure 2. Reconstruction of aircraft position P by iterative ray-triangulation of output data series from two antennas (M and S).

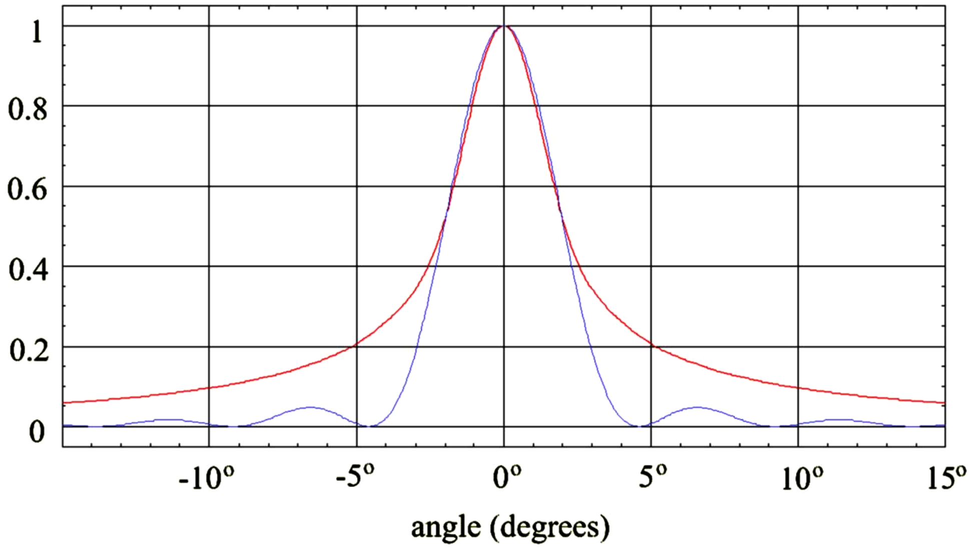

Figure 3. Beam simulations of a linear array antenna with 25 microphones at distance 7 cm for frequency 2400 Hz (blue) and for white noise (red). Directivity Index DI values are 15.8 dB and 13.0 dB respectively.

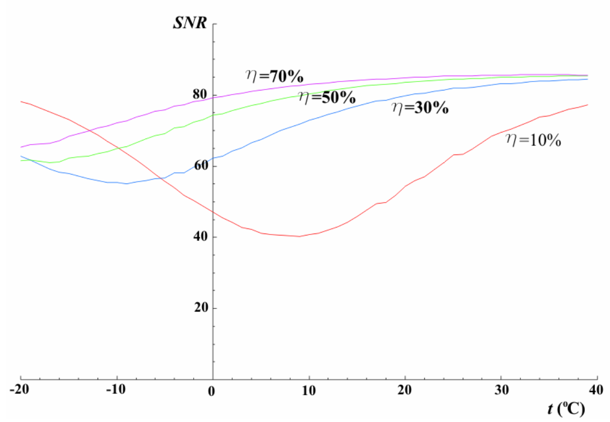

Figure 4. Simulated *SNR* at ATZ border (2.5 NM) vs. air temperature *t* in function of the relative humidity *η* (aircraft KC-135, approach, v=80 m/s, *f*<2.5 kHz, L_{AMAX}=95.4 dBA at 60 m).

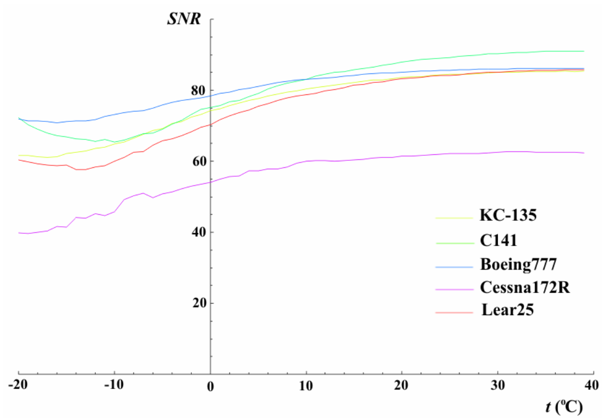

Figure 5. Simulated *SNR* at ATZ border (2.5 NM) vs. air temperature *t* for different aircraft models during approach operation (*η*=50%, *f*<2.5 kHz).

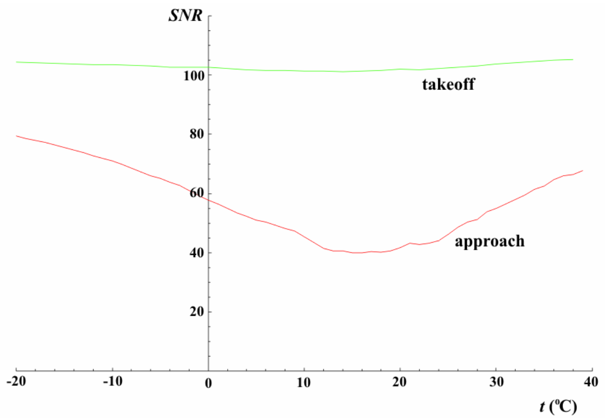

Figure 6. Simulated *SNR* at ATZ border (2.5 NM) vs. air temperature *t* for different Boeing 777 airport operations (*η*=10%, *f*<5 kHz).

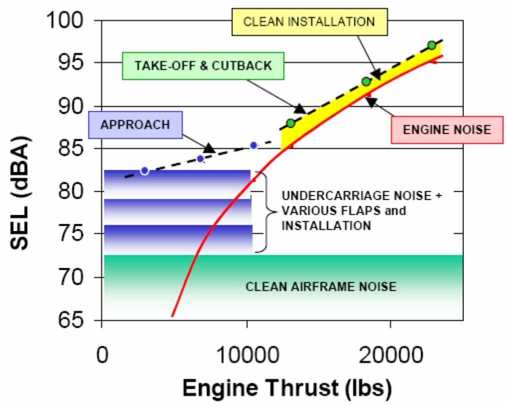

Figure 7. Typical NPD curve (Noise-Power-Distance) showing the aircraft noise level (SEL) at a given distance vs. engine thrust for different aircraft operations. Contribution of aircraft engine, settings and clean airframe to the total noise are also shown.

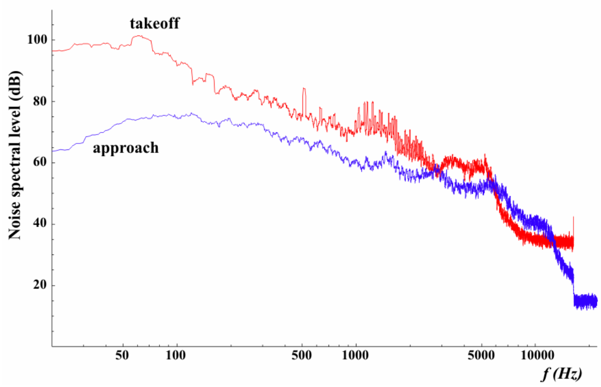

Figure 8. Noise spectrum of a Boeing 777 in simulated approach (v=70 m/s, L_{AMAX}=94.8 dBA at 60 m) and takeoff (v=-80 m/s, L_{AMAX}=108.3 dBA at 60 m).

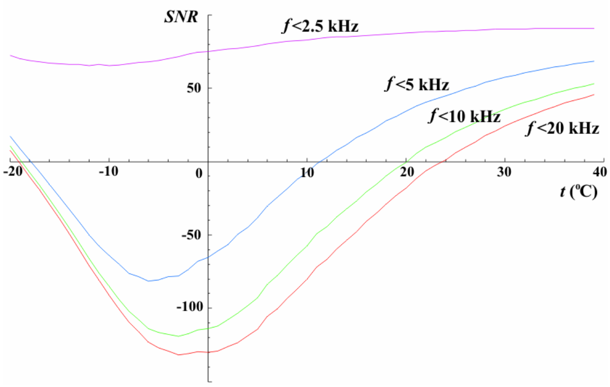

Figure 9. Simulated *SNR* at ATZ border (2.5 NM) vs. air temperature *t* for different high-frequency cutting filters (aircraft C141, approach, v=70 m/s, *η*=50%).

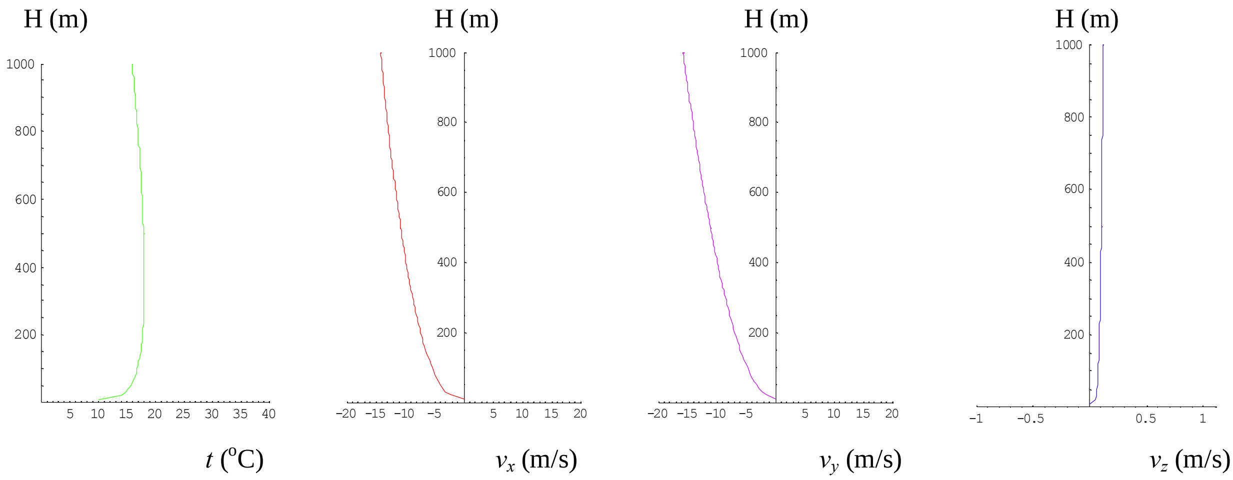

Figure 10. Profiles (with altitude H) of temperature t and of wind speed components v_x, v_y and v_z used as input data for the 3D simulation shown in Figure 11. Test scenario: temperature inversion and strong wind gradients.

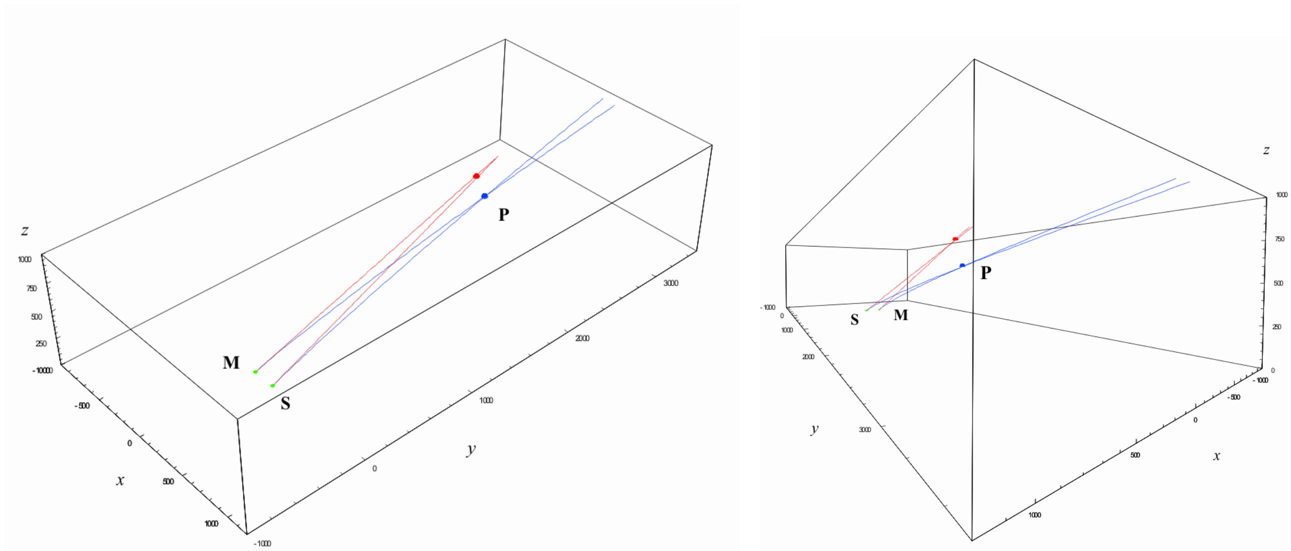

Figure 11. 3D simulation of corrected aircraft position (blue point) taking into account deviated acoustic rays (blue rays) for air temperature and wind gradients (see Figure 10). Uncorrected aircraft position is shown in red. The two green spots on ground represent the two SAFE-AIRPORT antennas. 3D simulations can be visualized from different points of views (right) or through rotating animations. All distances are in m.

TABLE 1									
input					output				
τ	θ_M	φ_M	θ_S	φ_S	x_P	y_P	z_P	d_{MP}	r
1	23.5	3.8	23.0	-1.5	140.8	2023.0	650.0	2128.9	404.7
2	22.5	4.0	20.5	-1.7	139.3	1935.8	570.0	2022.2	503.7
3	21.9	4.3	19.8	-1.9	137.3	1763.0	500.0	1837.1	216.1
4	21.0	4.5	18.7	-2.2	132.7	1625.6	430.0	1686.2	173.6
5	20.3	4.7	18.0	-2.3	133.2	1557.3	390.0	1610.4	222.8
6	20.0	5.0	17.7	-2.5	133.9	1510.3	370.0	1560.3	329.3
7	19.9	5.3	17.5	-2.7	133.2	1434.0	350.0	1481.7	330.7

Table 1. Example of simulation results. Model input data from antennas M and S referred to M time steps τ: elevation θ_M and θ_S; azimuth φ_M and φ_S. Simulation output: corrected aircraft position P coordinates x_P, y_P, z_P; distance d_{MP} of P from antenna M; error r in terms of distance of P from uncorrected position.

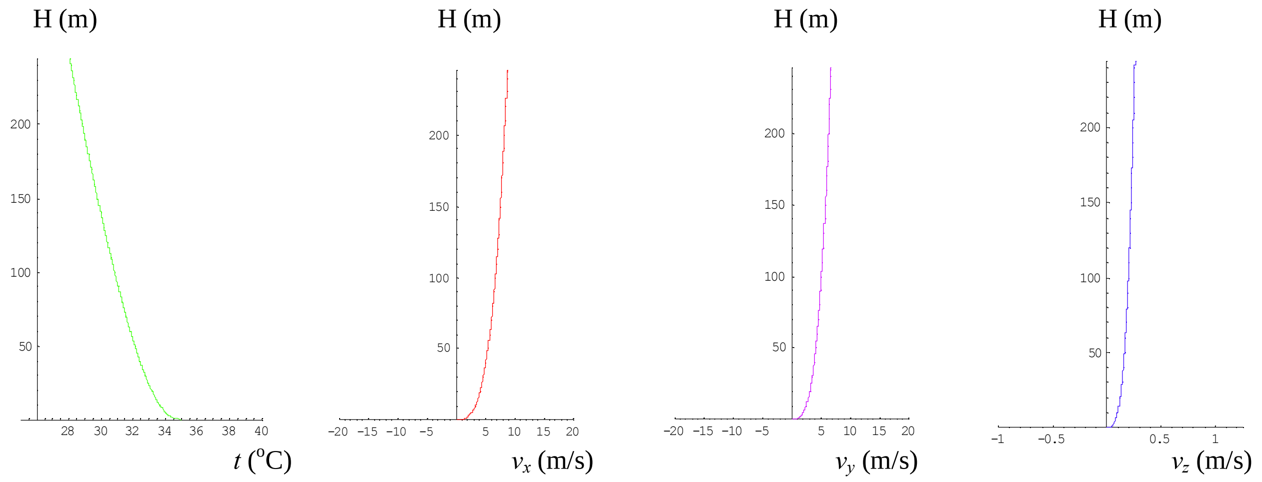

Figure 12. Profiles (with altitude H) of temperature t and of wind speed components v_x, v_y and v_z used as input data for the 3D simulation shown in Figure 13. Test scenario: temperature super-adiabatic and strong wind gradients.

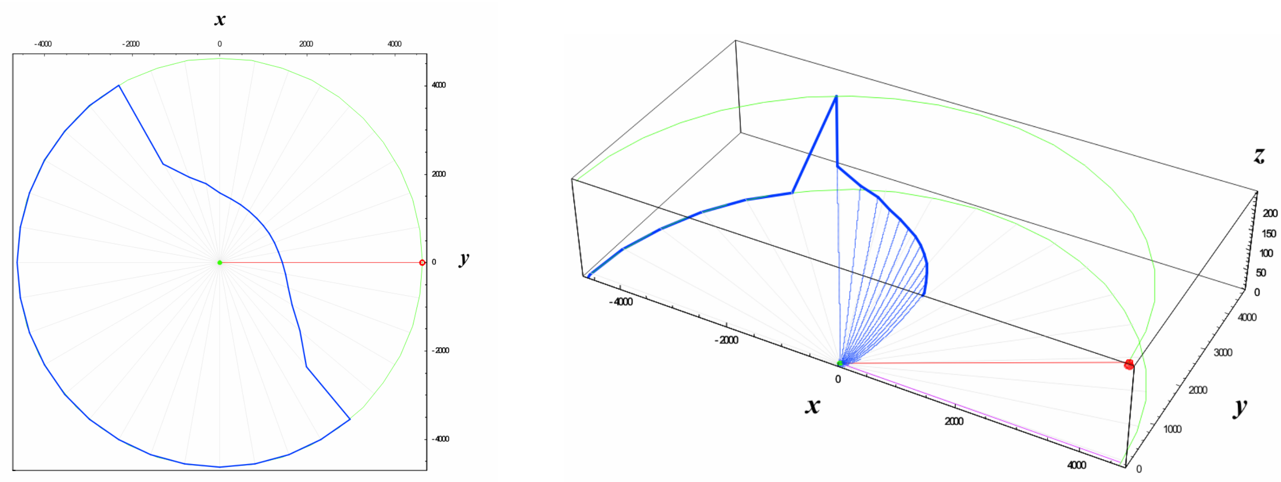

Figure 13. Acoustic shadow simulation within an ATZ of 2.5 NM radius (border in green) for one antenna (green spot on ground in the ATZ center) with atmospheric profiles of Figure 12 as input data. A typical aircraft approach trajectory with descent angle of 3º is simulated (red). In the horizontal plane section at H=250 m (left) the points within the blue line are shadow-free. The 3D view on the right shows a vertical plane section at y=0. Altitude z is not in scale with ground coordinates x and y. All distances are in m.