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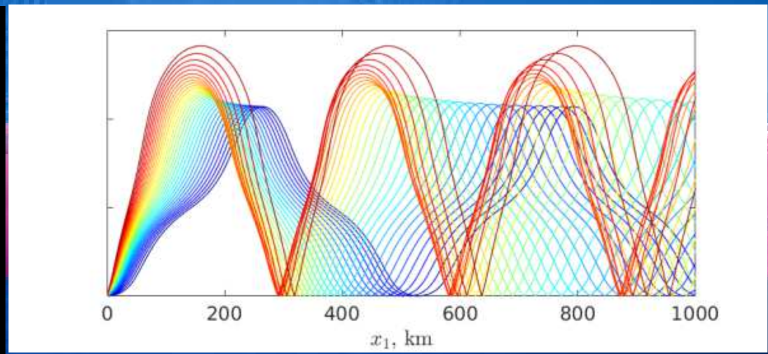


CeLyA Summer School «Atmospheric Sound Propagation»

13-15 June 2018, Lyon

Engineering models: application to aircraft noise

P. Malbéqui

ONERA, Aerodynamics, Aeroelasticity and Acoustics Department, France

ONERA

THE FRENCH AEROSPACE LAB

retour sur innovation

Outlines

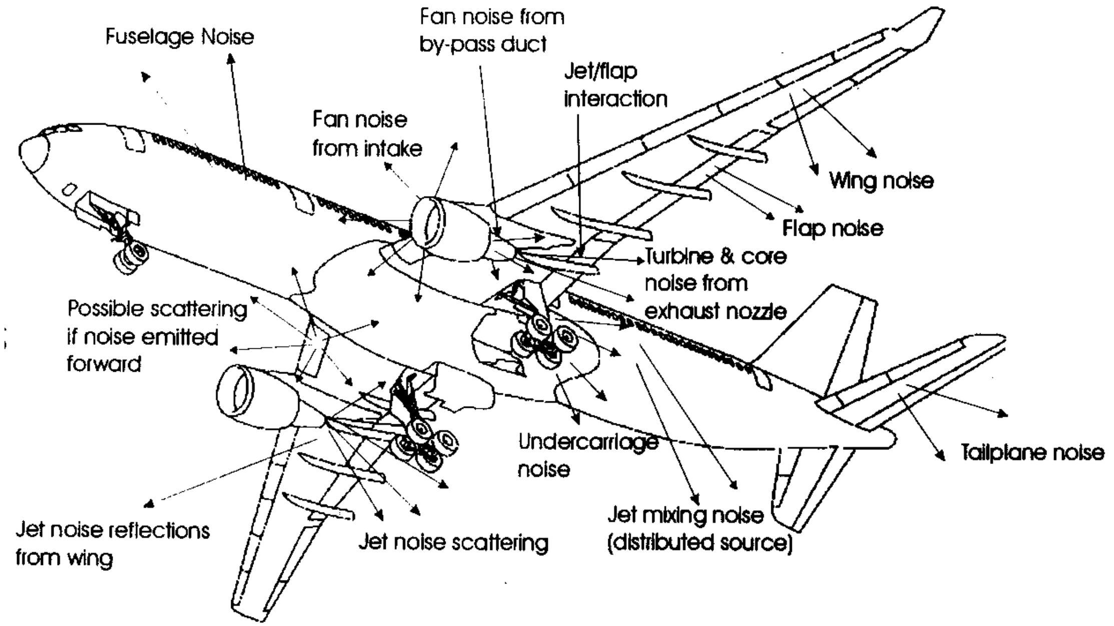
- Context
- Modelling the aircraft noise in CARMEN
  - Noise source
  - Installation effects
  - Atmopsheric sound propagation
- Assessment and application:
  - A340 at landing
  - A320 at take off
  - Contra rotative propeller (CROR), a non existing A/C
- Summary

Presentation dedicated to Y. Rozenberg for his significant contribution

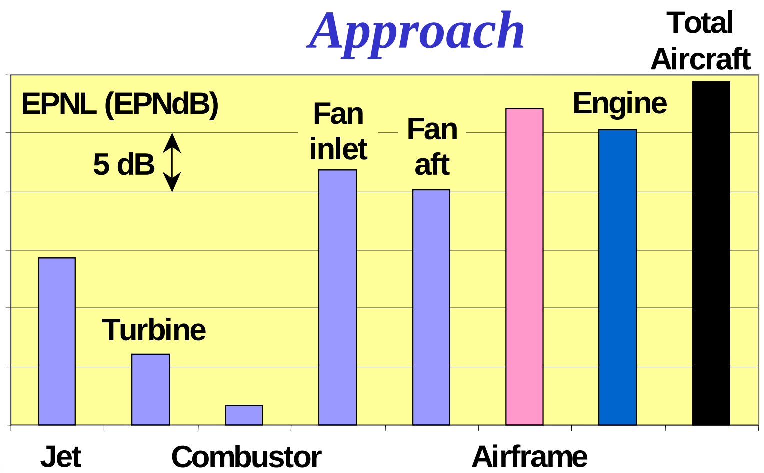
Context

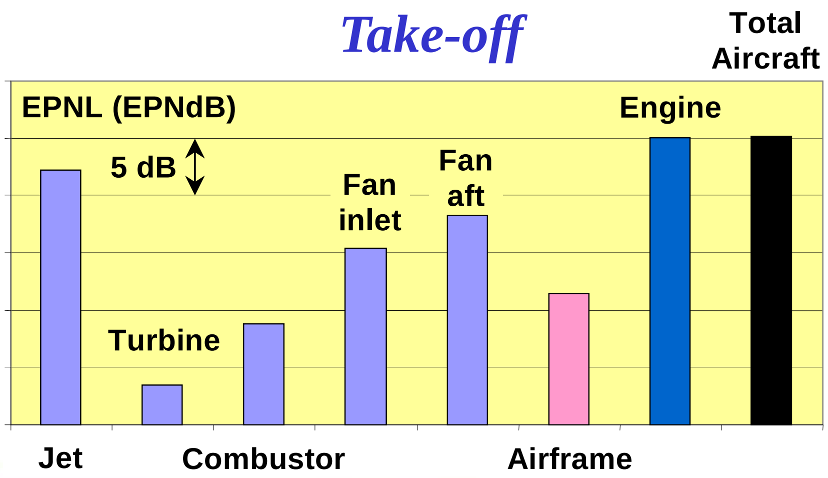
- Pressing demand to decrease noise impact around airports due to the increase in air traffic
- Technical advance becoming more difficult to reduce the noise footprint
- Emergence of new aircraft concepts and new approach and landing procedures required

Context:
Acoustical sources generated by an aircraft



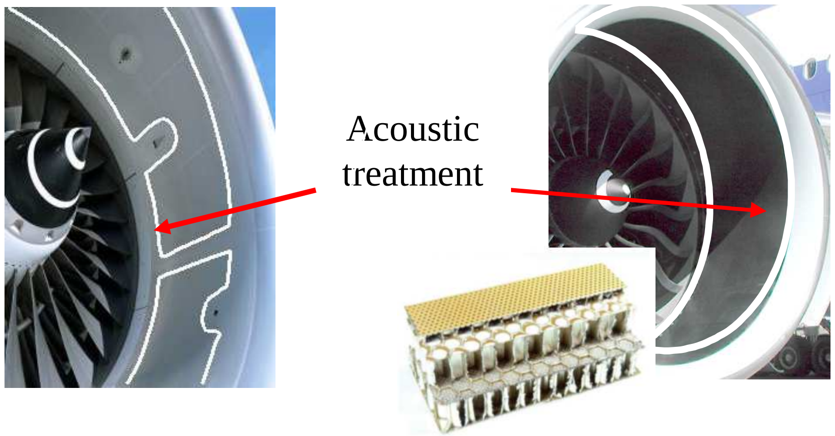
- At take-off : the engine noise is dominant.
- At approach/landing: engine and airframe contributions are about the same.





Context:
Examples of technologies to reduce the A/C noise

Optimisation of the surface of the liner to reduce fan noise



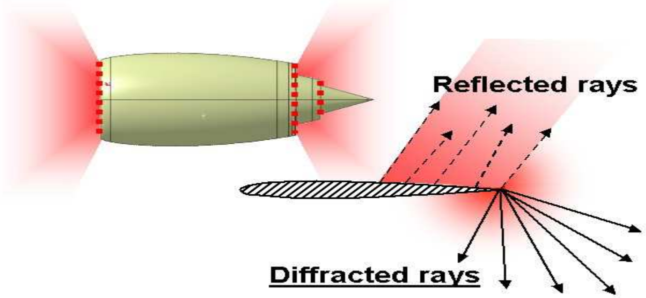
Chevrons at the exhaust to reduce the jet noise

Scarfed inlet to reduce the fan noise

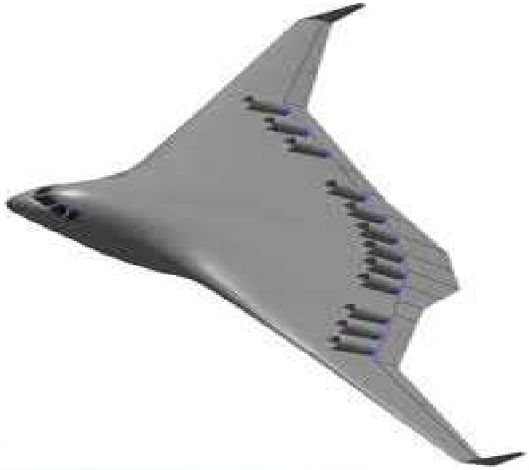
Landing gear including a fairing

Context:
Examples of new concepts to reduce the noise

Shielding by the structure



Distributed electrical engines



Prediction of aircraft noise with engeeriging models in CARMEN

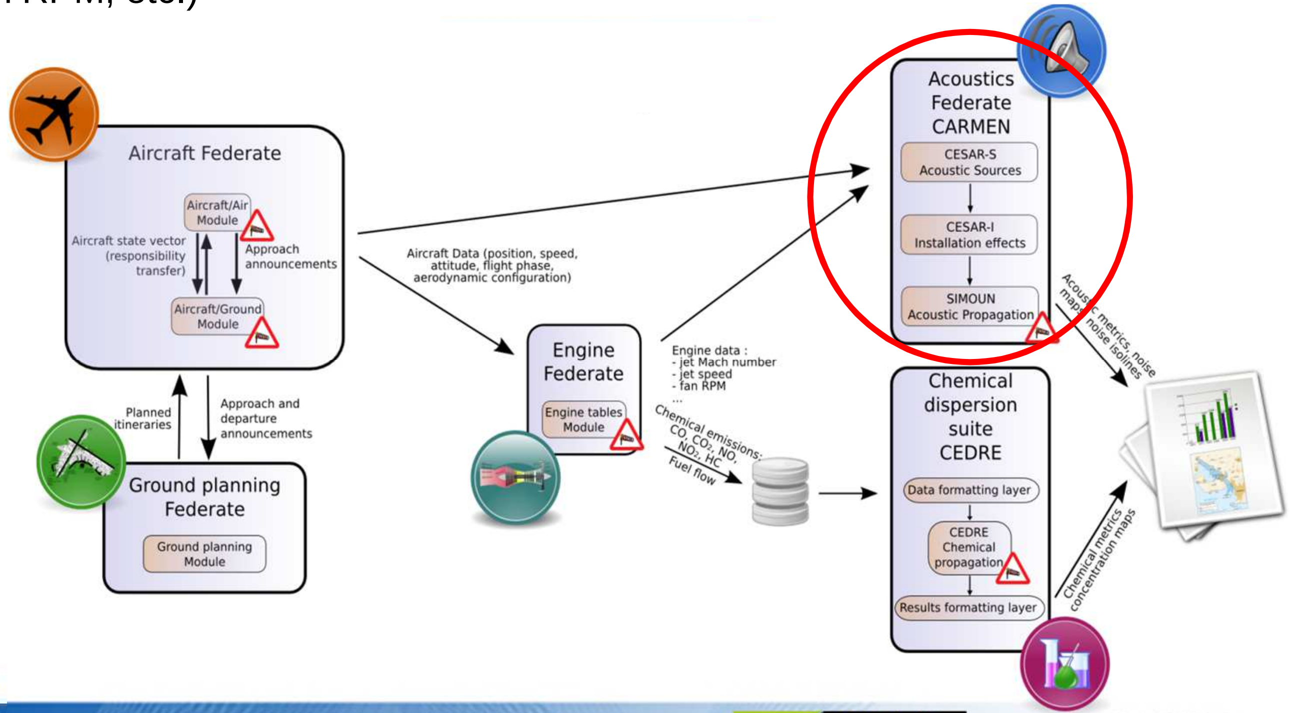
IESTA : Infrastructure for Evaluating Air Transport Systems

Challenge:

To accommodate the increase in air traffic, reducing the impact of aviation, with respect to noise around airport, chemical emissions and fuel consumption

Models implemented in the IESTA plateform

- Aircraft (position, speed, aerodynamics configuration)
- Ground planning
- Engine (Jet Mach Number, fan RPM, etc.)
- Chemical dispersion
- Acoustics (CARMEN)



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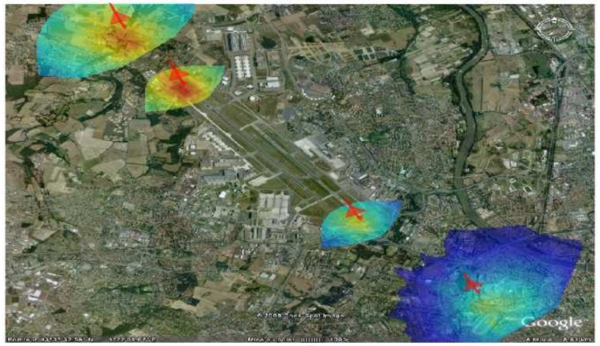
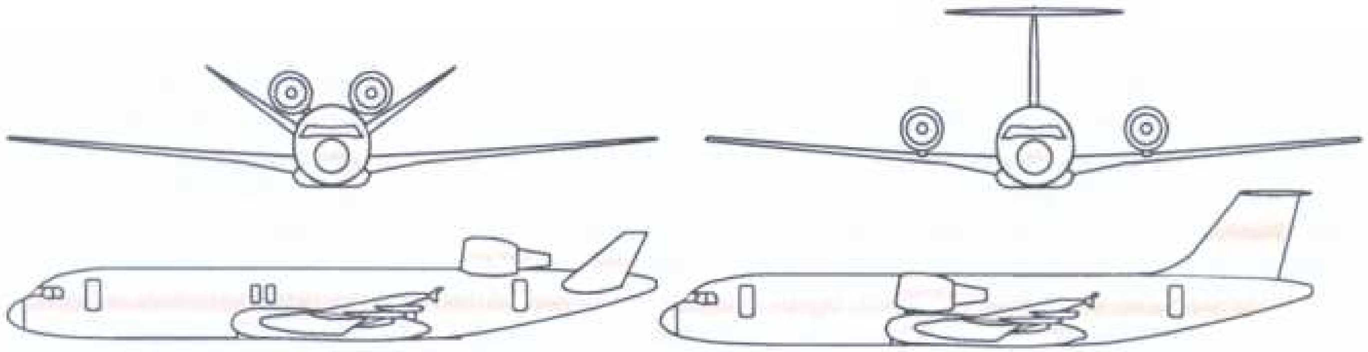
CARMEN : Acoustics in IESTA



Objectives:

- To predict the acoustical impact of an aircraft surrounding airport
- To take into account new technologies and noise sources (shielding effects, contra-rotative propellers, etc.)
- Simulations within a « reduced » CPU time
- To generate realistic temporal signature, as input for perception and annoyance studies



Installation effects

Modelling and assessment of the acoustics predicition

Modelling:

- Analytical models: provide the main parameters driven the physics
- Empiricals & semi-empirical and models: accurate tools to predict the far field on a limited application domain
- Computational Aero Acoustics (CAA) for checking the propagation models

Assessment:

- Wind tunnel tests
- Flyover experiments
- Noise source identification using a microphone phase array, during a/c flyover

3 acoustic modules :

- Noise sources: airframe noise + engine noise in free field
- Installation/shielding effects induced by aircraft surfaces
- Atmospheric sound propagation

Structure of the acoustics modules in CARMEN

Pre-processing

Static parameters

•Aircraft geometry

•Volume simulation (x ,y ,y)

•Meteorolical conditions

Installation effects

Propagation in the atmosphere

Database.1

Database.2

Simulation

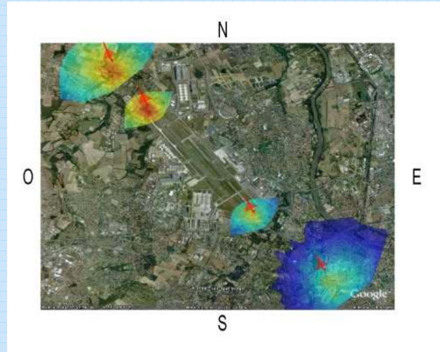
Dynamic parameters
At each time step of the aircraft trajectory :
• aircraft configurations (engine RPM, jet, slat, flap, landing gear conditions, etc.)

Acoustical sources

CARMEN concatenation

Database.3

Post-processing



Outputs:
•Footprints
• SPL
• spectra
• metrics

Modelling:
Noise Sources

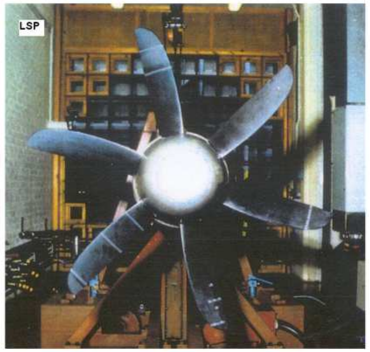
Acoustical sources implemented in CARMEN

Airframe noise

- High Lift Devices: slat & flap
- Landing gear

Engine noise

- Fan inlet and aft
- Jet (single & coaxial)

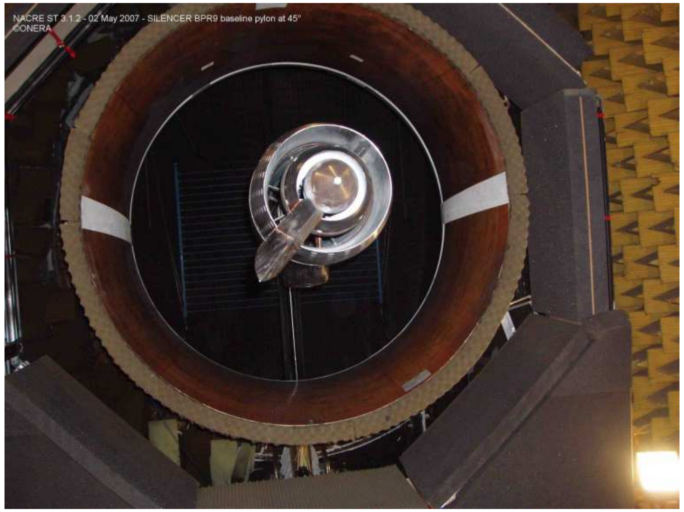


- Propeller

Noise source modelling:
Coaxial jet noise prediction

- Semi-empirical coaxial jet noise model: [Stone *et al.*, AIAA J. (21), 1983]
  - already validated in static conditions

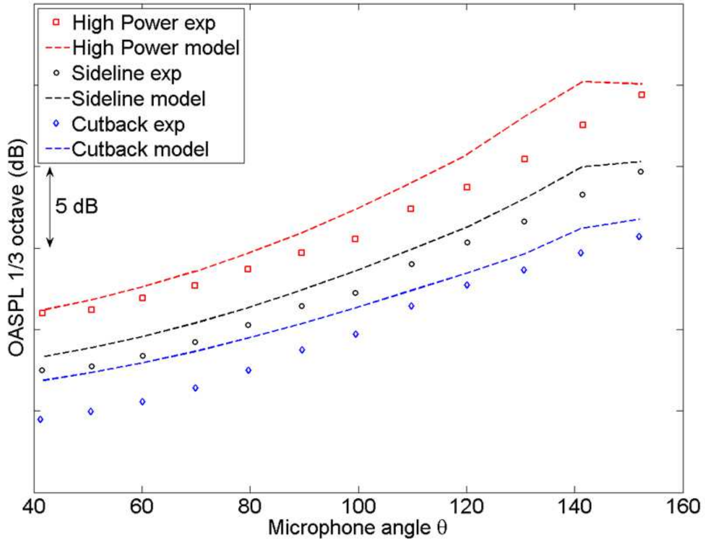
- Comparison with experimental results from the EU-project VITAL:
  - 3 jet conditions (High power, sideline and cutback)
  - Static and flight conditions



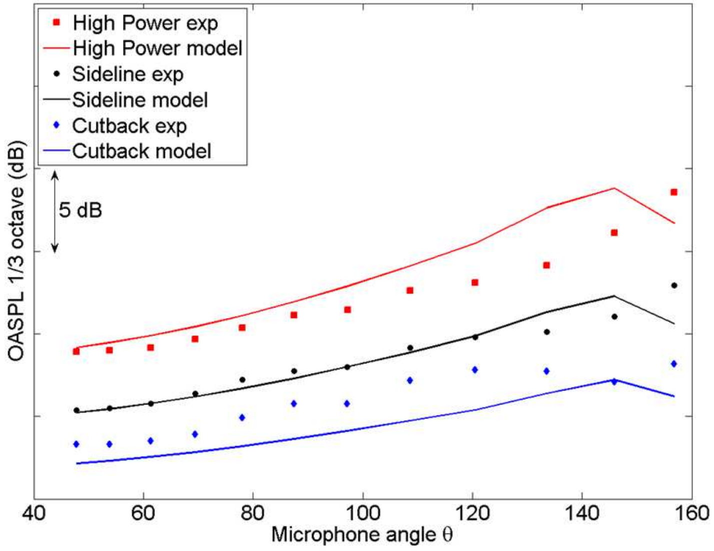
Jet noise in CEPRA-19 Wind Tunnel

Noise source modelling

Coaxial jet noise prediction



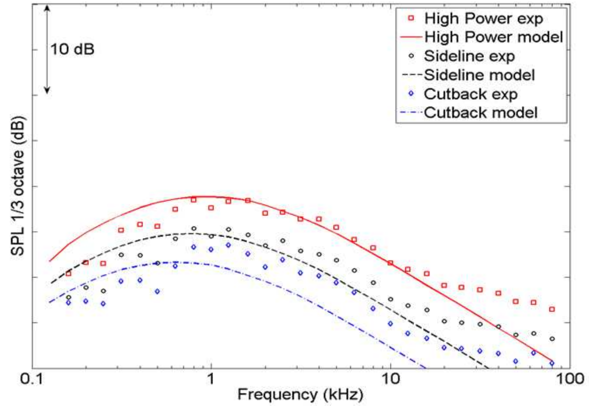
Static condition



Flight condition

Model ◻ Exp

- Good agreement between model and experiments
- As expected, flight effects tend to decrease jet noise, especially in the aft region (up to 8 dB)

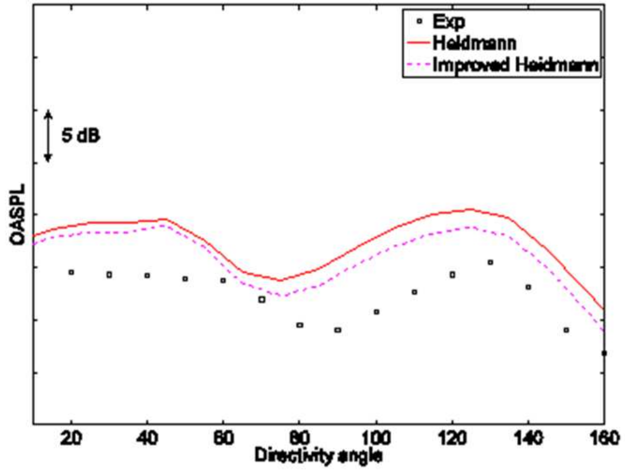


Spectra

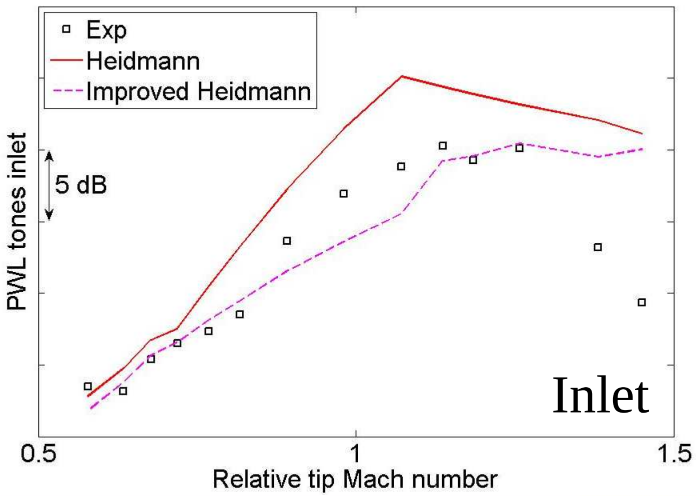
Noise source modelling:
Fan noise

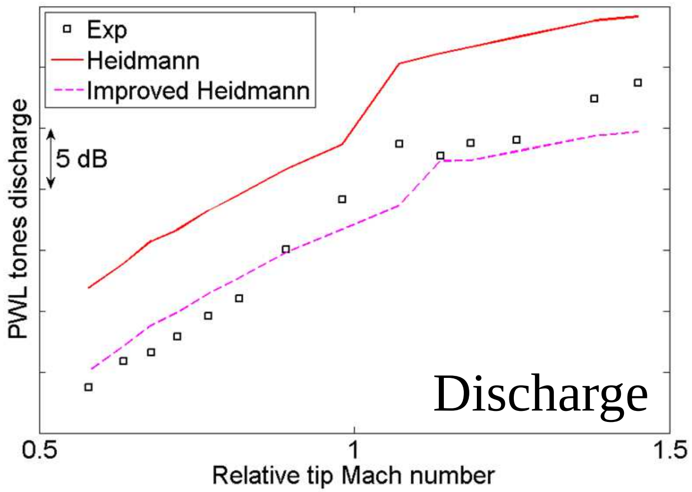
[Heidmann, NASA TM-X-71763, 1979]

OASPL (tonal+broadband) directivity



Tonal power noise level *vs* the relative tip Mach number

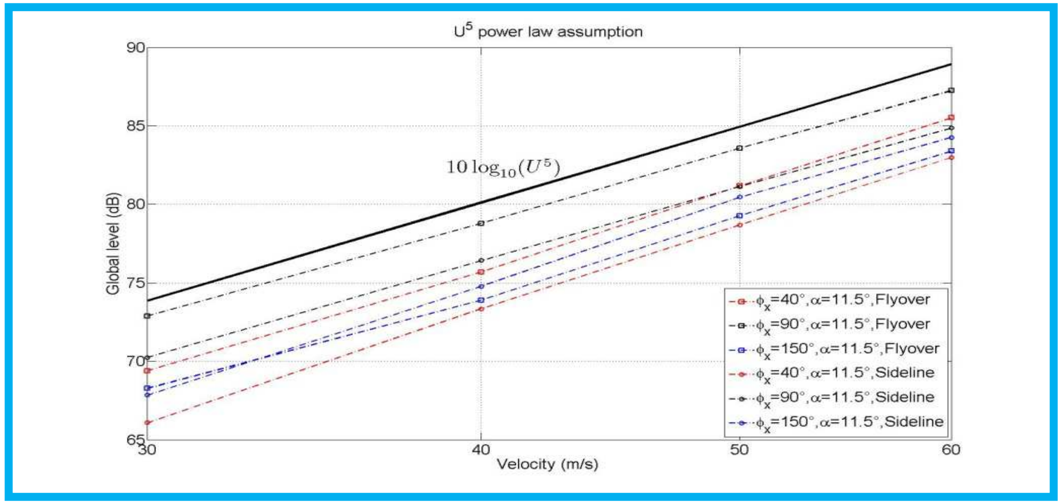




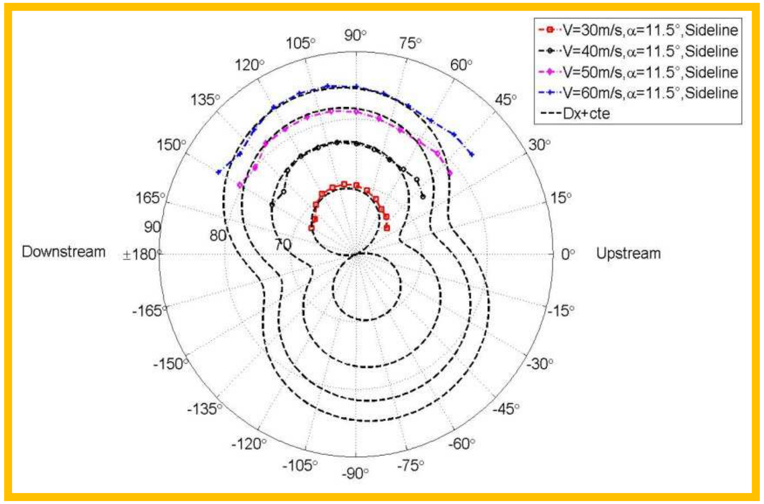
Noise source modelling: Slat noise

[Dobrzynski *& al.* model (2001)]

- Assessement and tuning of the model from TYNPAN project against Measurement in Cepra19 W-T
- Directivity, speed, steering angle



OASPL versus flow velocity, V^5 law



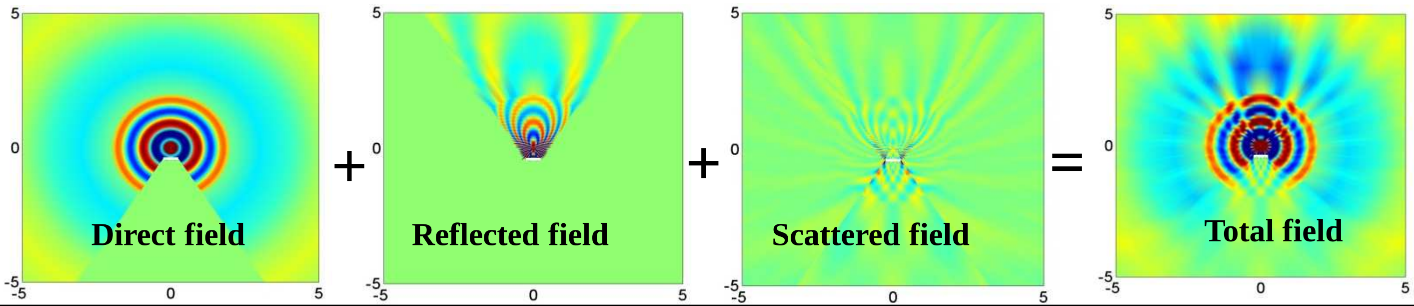
Dipolar directivity

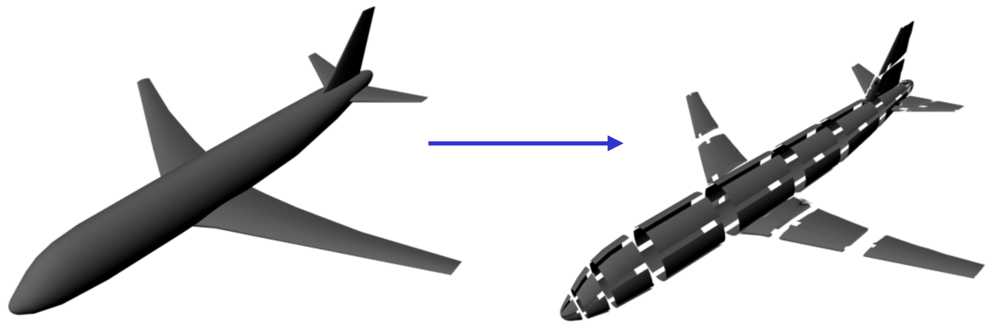
Modelling : installation effects

Installation effects

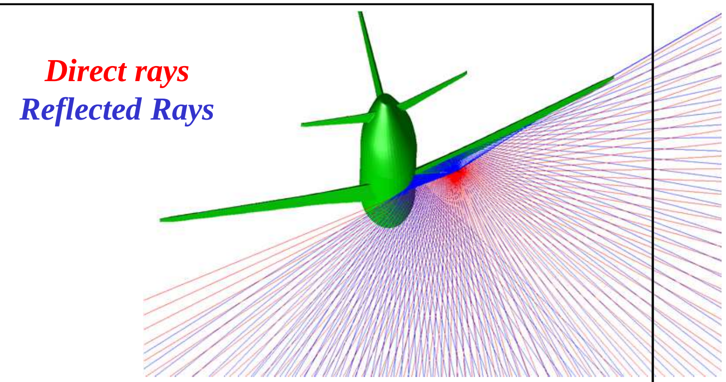
Model based on the ray tracing technique

1- Direct + Reflected + Diffracted field from Uniform Theory of Diffraction
Scaterring by the edges (leadind edge) et creeping waves (fuselage)





2- Geometry described from analytical curves surfaces (NURBS) from CAD files

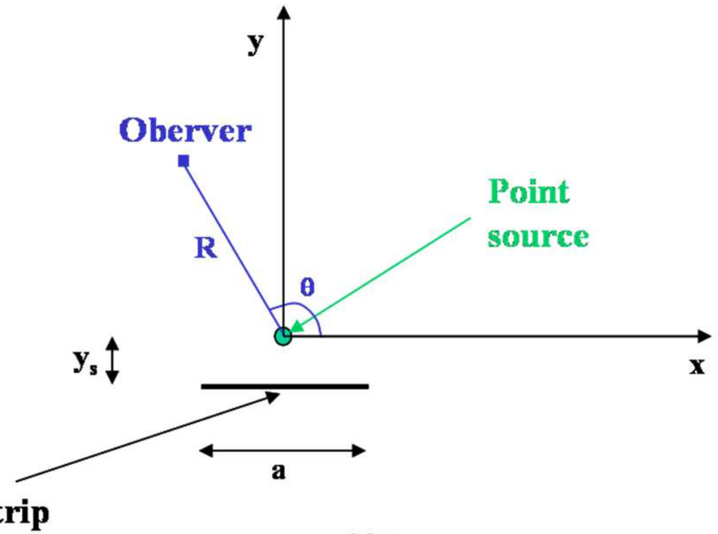


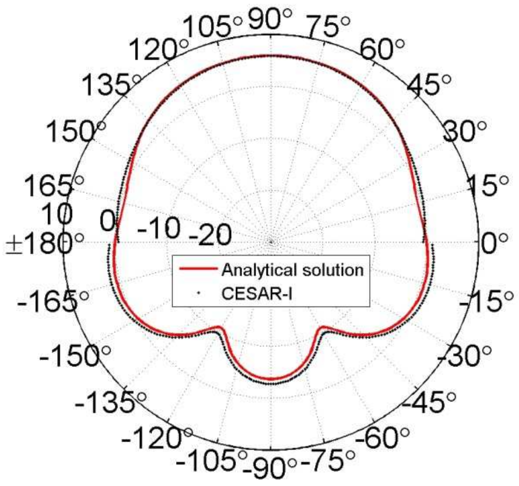
3 - Ray paths performed using Fermat principle

[Malbéqui, Rozenberg & Bulté, Internoise-2011]

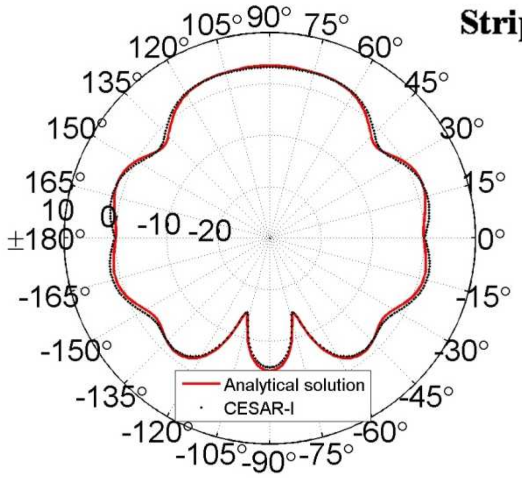
Diffraction by a strip

- Analytical solution : sum of Mathieu functions.
- [Bowman & al. , Electromagnetic and acoustic scattering by simple shapes, 1969]

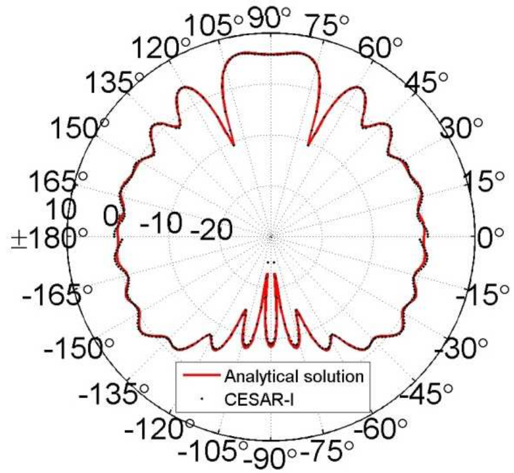




ka = 4,6



ka = 9,2



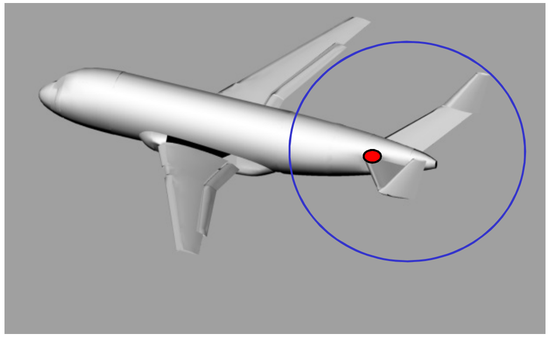
ka = 27,7

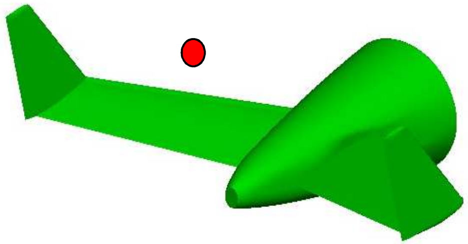
Reflection coefficient, $|p_i+p_r/p_i|$ (dB)

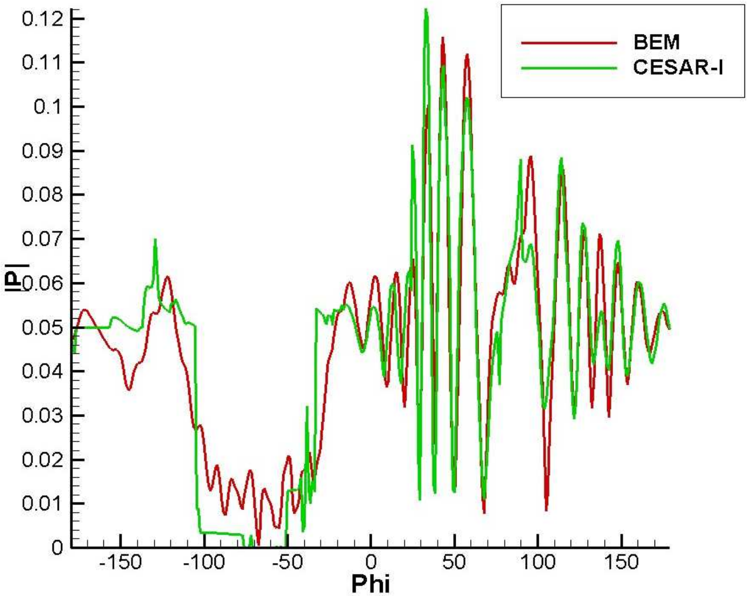
Installation effects:
CARMEN / Boundary Elements Methods (BEMUSE)

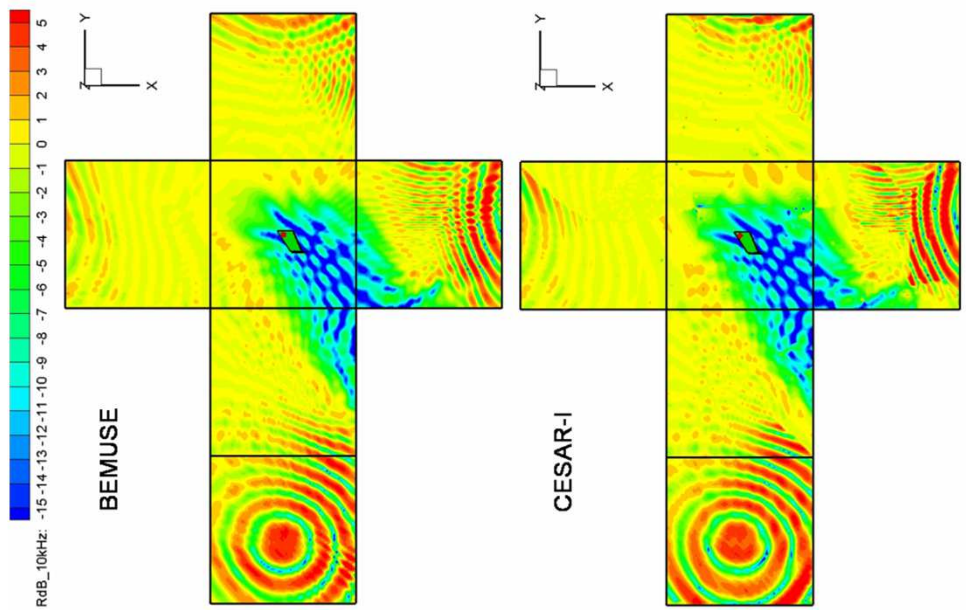
Diffraction by the edges of the empennage

F = 1 kHz (~BPF of the fan)



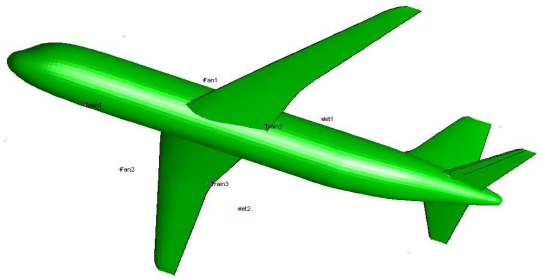




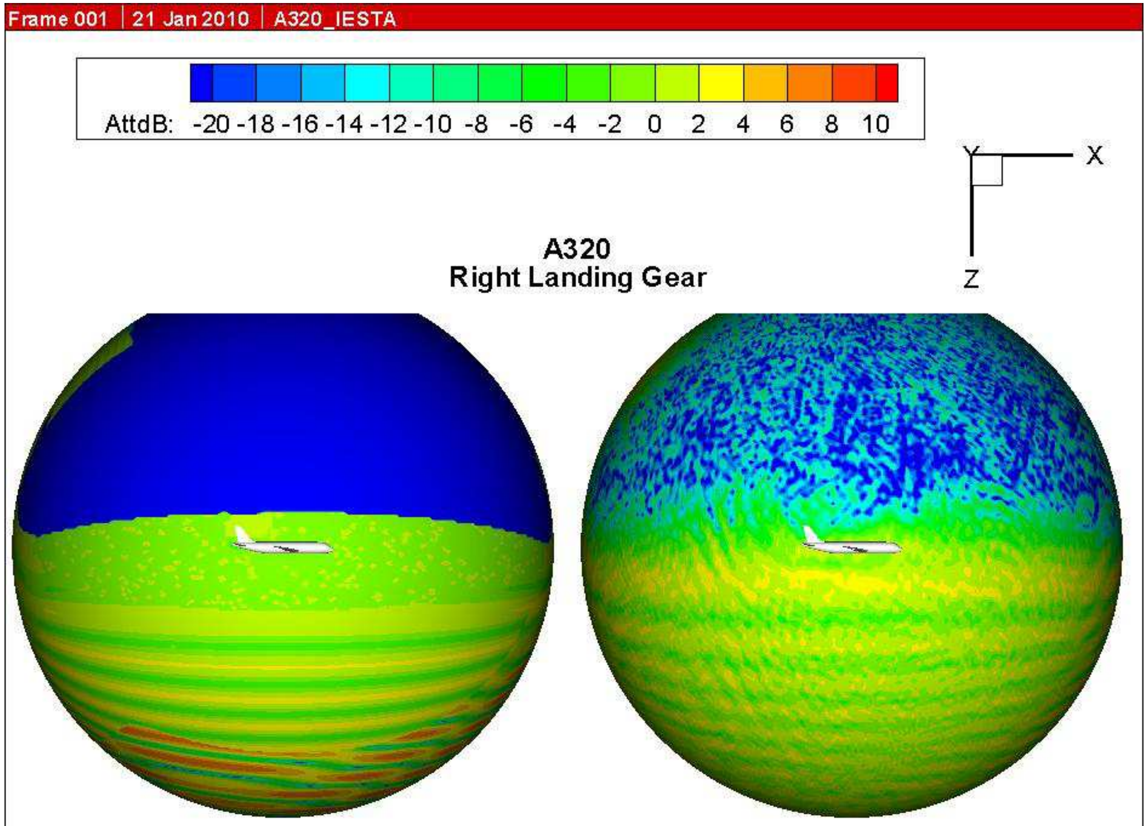


BEMUSE CARMEN

Installation effects: on a whole aircraft
Comparison CARMEN /BEM (BEMUSE)



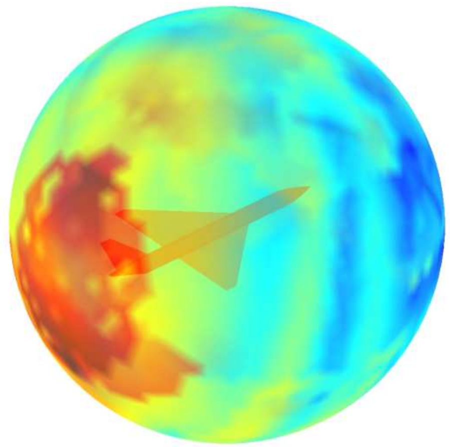
A320



CARMEN
(no scattering)

BEMUSE

Coupling acoustical source models and installation effects



Objective:

- Prediction of the noise on a sphere surrounding the aircraft including installation effects, to provide the input of the sound propagation in the atmosphere

Assumptions:

- Source modellling: free field noise model (strength and directivity)
- Source considered as directive monopole
- Green's function including reflections and diffractions given by the ray-method

Coupling acoustical source and installation effect

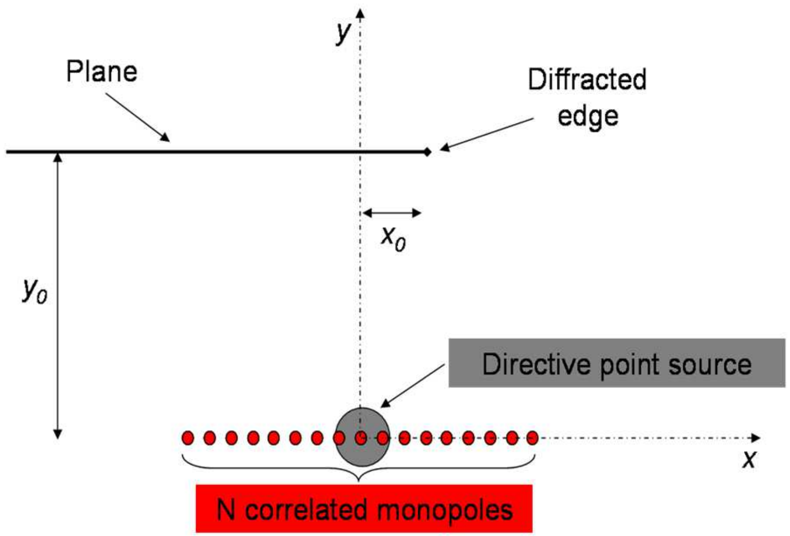
Is the coupling still accurate when:

- The source is extended (jet noise)?
- The source is close to the diffracting surface ?

Source model:

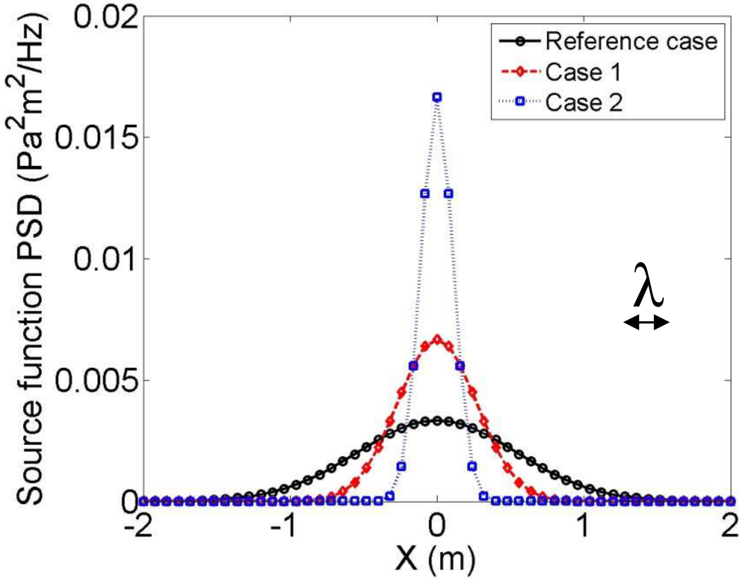
- Extended source described with N correlated monopoles: s_i
- Exponential spatial coherence model :

$$S_{ij} = \sqrt{s_i s_j}\,\exp\left(-\left(\frac{x_j - x_i}{\Lambda}\right)^2\right)$$

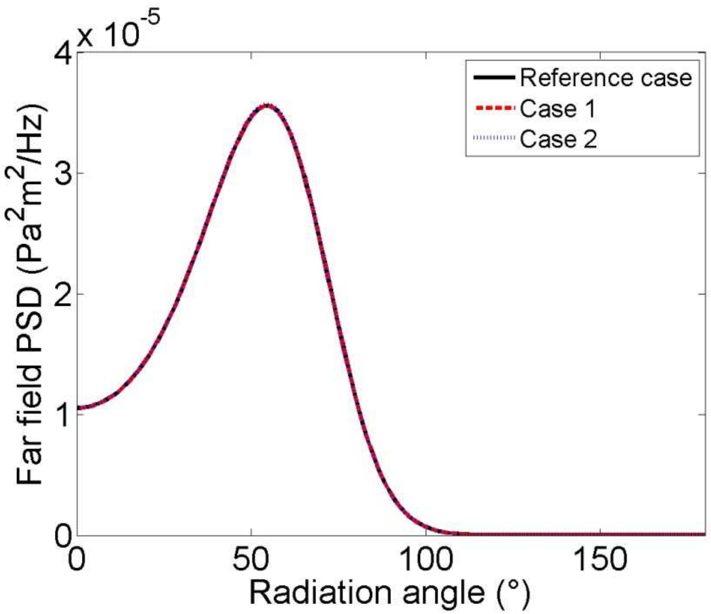


[Rozenberg, Bulté, Internoise 2008]

Source models: 3 sources distributions having the same far-field directivity pattern

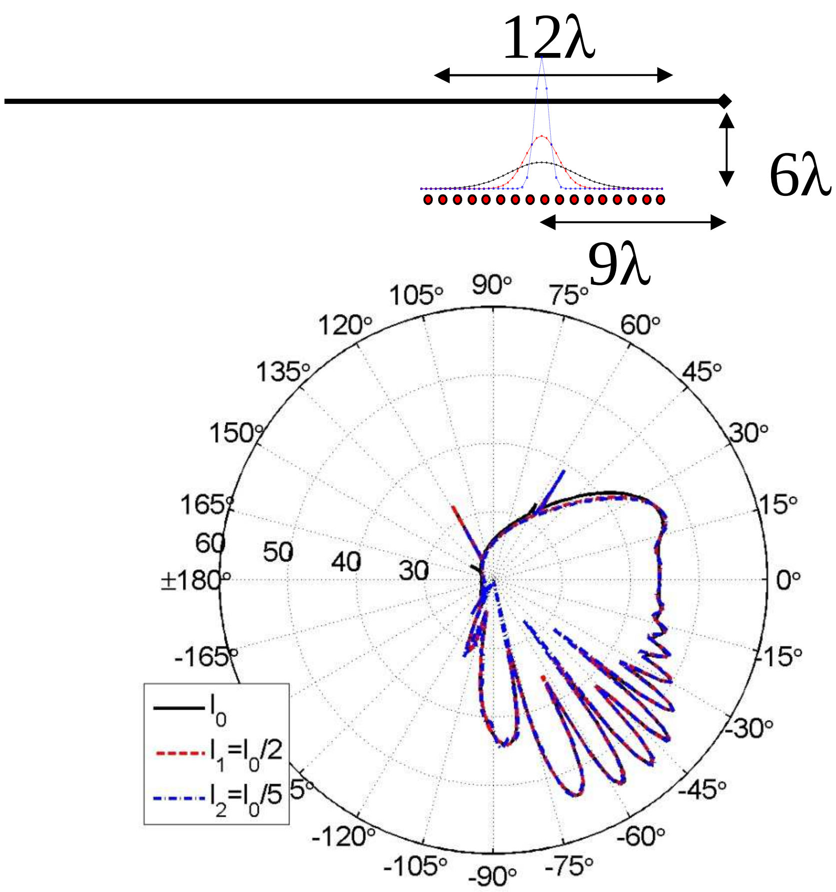


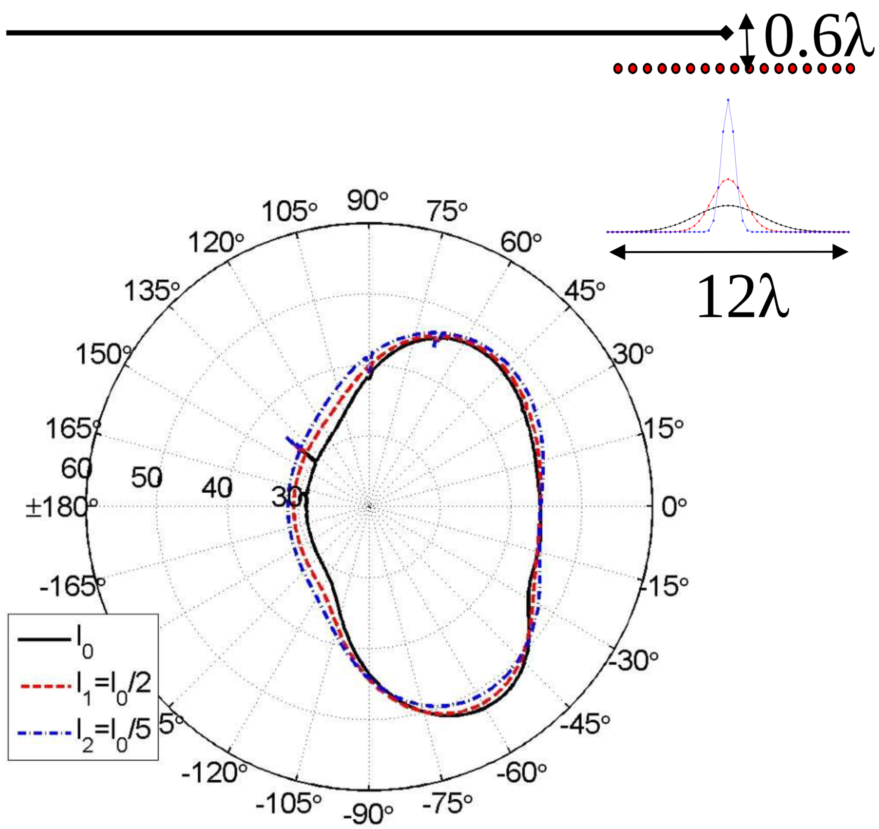
Source distributions



Radiation in the far-field

Coupling source radiation and installation effect
Effect of the source extension



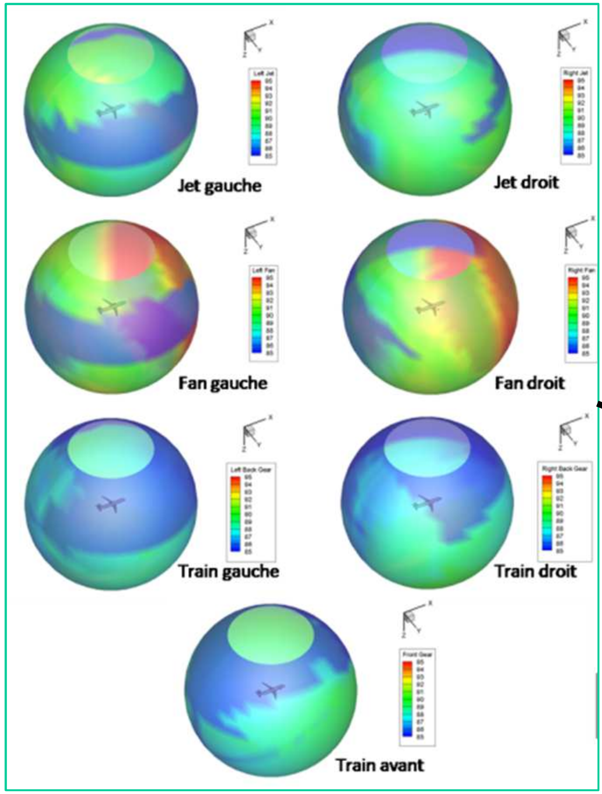


No effect when the source is «far» from the edge

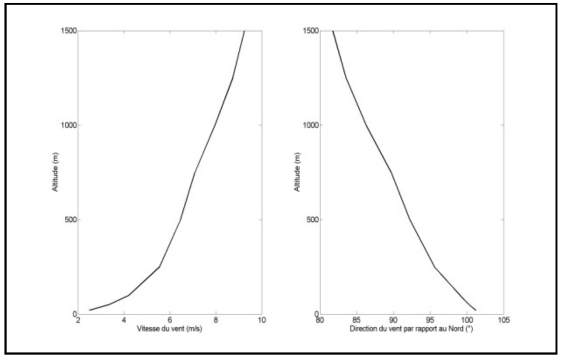
Noticeable (but not significant) effect when the source is close to the edge

Sound propagation in the atmopshere

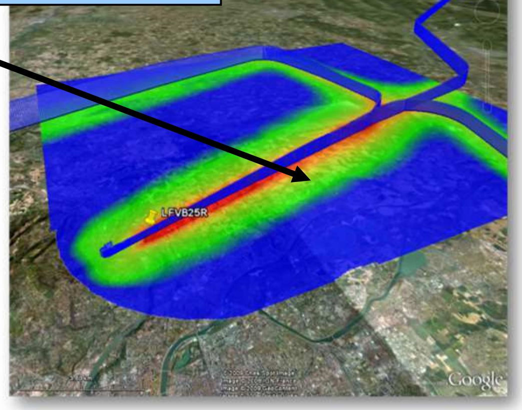
Chaining (source+installation) with atmopsheric sound propagation



Sources (jet, fan, landing gear)
+ installation effects

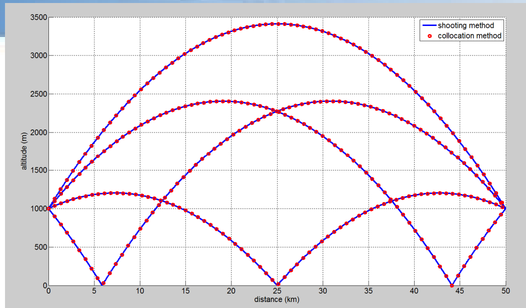


Propagation in the atmosphere:
- wind & temp. profiles
- atmospheric absorption



SPL footprint, 3 approach trajectories

Sound propagation in the atmopshere using ray-tracing

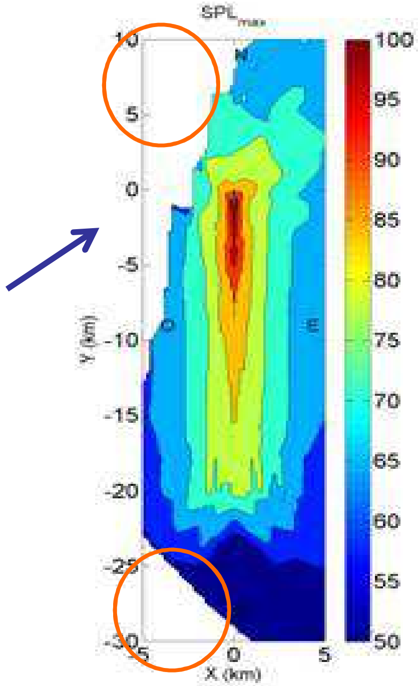


Standard Direct shooting method : ray-path from the source towards the microphone

- Initial Value Problem (source & direction of the wave vector)
- Partial Differential Equations (PDE) in time
- Ray shooting : equations integrated using a Runge-Kutta method of 4th order

Interest of the ray-method:

•Physically shows the acoustical power distribution in space
•The ray-path doesn't depend on the frequency of the aircraft source : significantly reduces the CPU time in the bandwidth of interest [50-10 000 Hz]
•Atmospheric absorption straigthforwardly computed along the ray paths



Footprint on the ground with shadow zones

Drawbacks (compared to the PE & the Euler's eqs)

•High frequency approximation
•No diffraction effects
•Presence of caustics : no result in the shadow zone (under upwind configuration or behind obstacles).

Sound propagation using the ray-method …

For the predictions to be compared with the experiments, we assume:

- Flat terrain, meteorological conditions not a function of the x-y location
- Meteoroligical conditions steady during the aircraft flying path
- No atmospheric turbulence

This allow to pre-process within a short CPU time the ray-paths computation for during the whole aircraft tarjectory

Assessment of CARMEN on flyover experiment:

A320 during take-off

Noise Flight Test Campaign on A320 – Moron Spain, Airforce base, 2004

Flight test of engine: noise reduction solutions

Baseline CFM Intake

Negative Scarfed Intake (NSI)

Aircraft at take-off, baseline intake

- Aircraft speed : 150 kt
- Engine power : 75 to 95 %
- Slat / Flap deflection : 18°/10°
- Landing Gear : Up

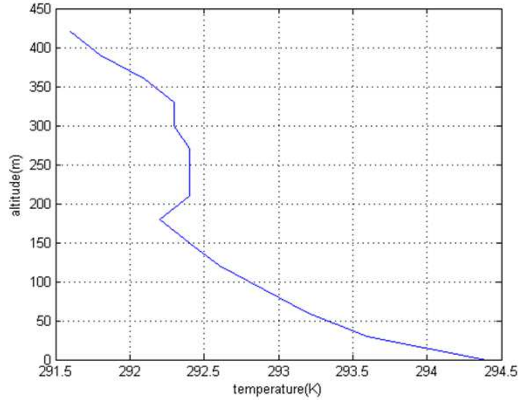
→ **Engine noise (Jet & Fan) predominant**

Meteorological measurements

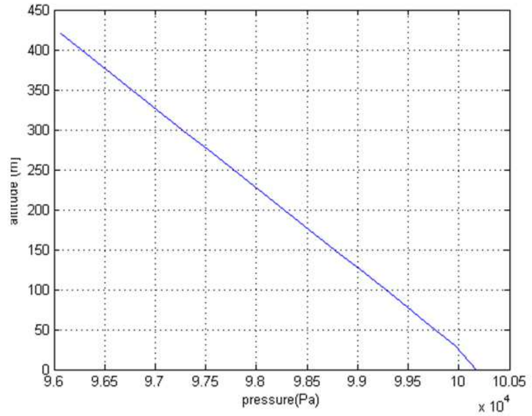
SILENCE(R)

Atmospheric measurements:

•Probes send out every 45 minutes



Temperature



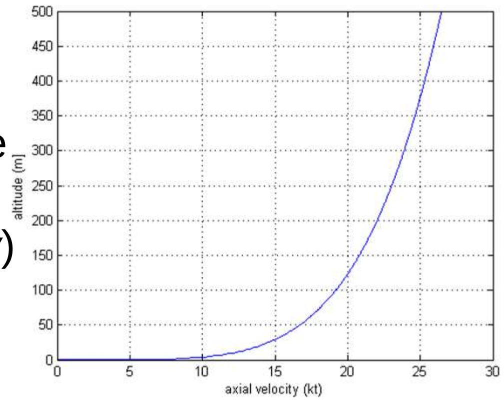
Pressure

Weather station:

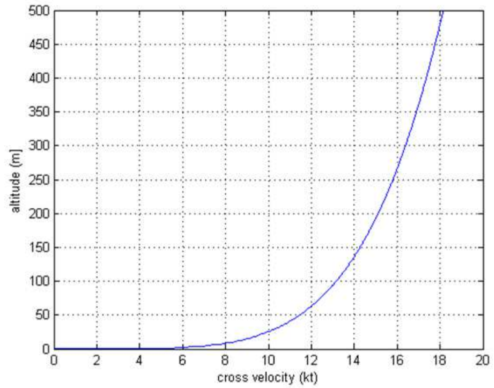
•On the runaway axis, 500 meters from the microphones

•10 meters weather measurements (*p, T, v*)

•*Wind velocity :* $V(z) = v_{10}*(z/10)^{0.2}$



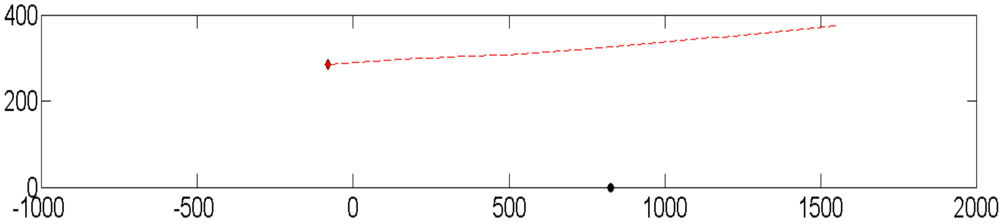
Axial velocity, v_{10} *= 12 kts*

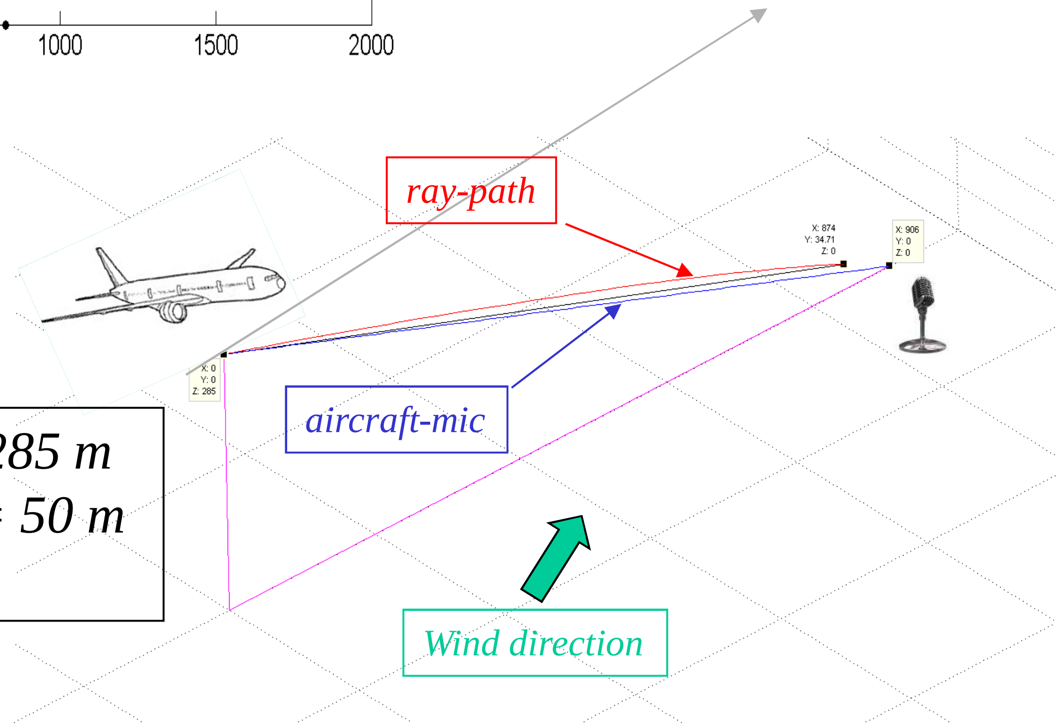


Cross velocity, v_{10} *= 8 kts*

Influence of the meteorological conditions (1/3)

Aircraft approaching the microphone

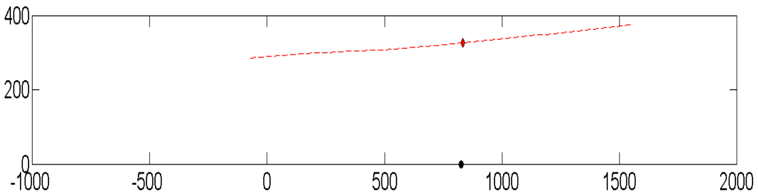


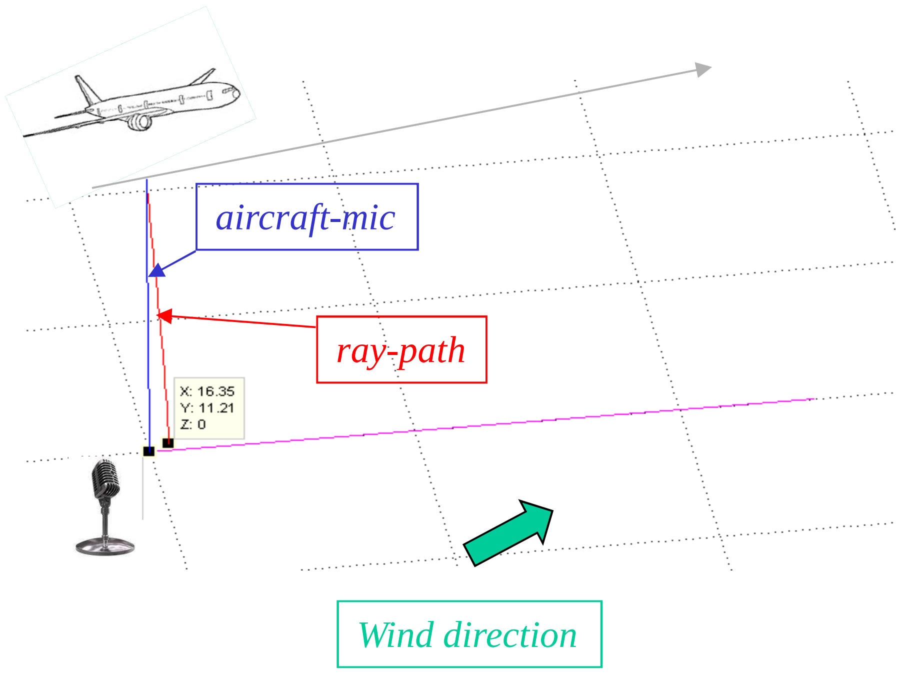


$d_{Aicraft\text{-}Mic} = 950m,\ z_{Aircraft} = 285\ m$
$\Delta(\text{ray-path} - \text{aircraft-mic}) = 50\ m$
$\Delta\ (1/r) = 0{,}4\ dB$

Influence of the meteorological conditions (2/3)

Aircraft directly above the microphone





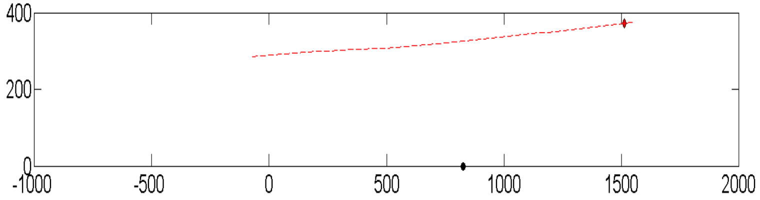
$d_{Aicraft\text{-}Mic}$ = 327 m, $z_{Aircraft}$ = 325 m

Δ(ray-path – aircraft-mic) = 20 m

Δ (1/r) = 0,5 dB

Influence of the meteorological conditions (3/3)

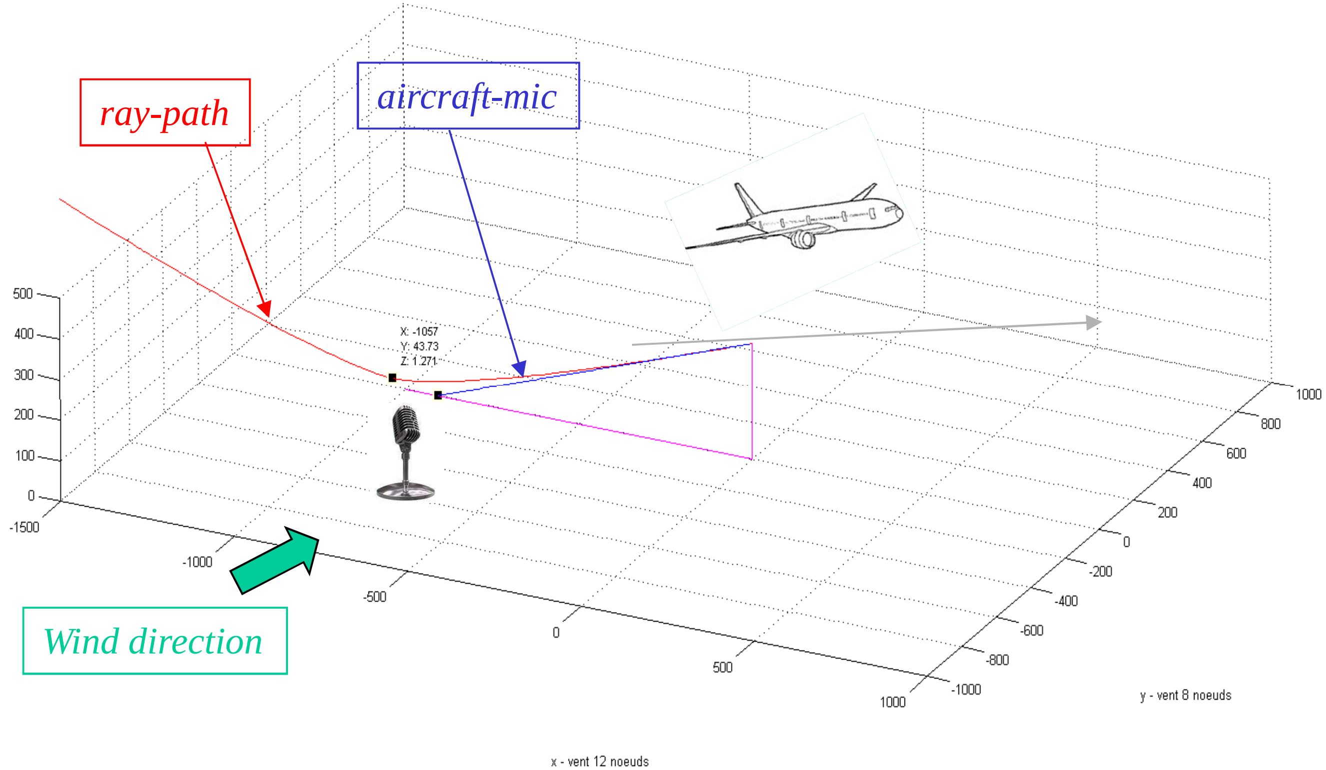
Aircraft moving away the mic



$d_{Aicraft\text{-}Mic} = 780m,\ z_{Aircraft} = 372\ m$

$\Delta(\text{ray-path} - \text{aircraft-mic}) = 157\ m$

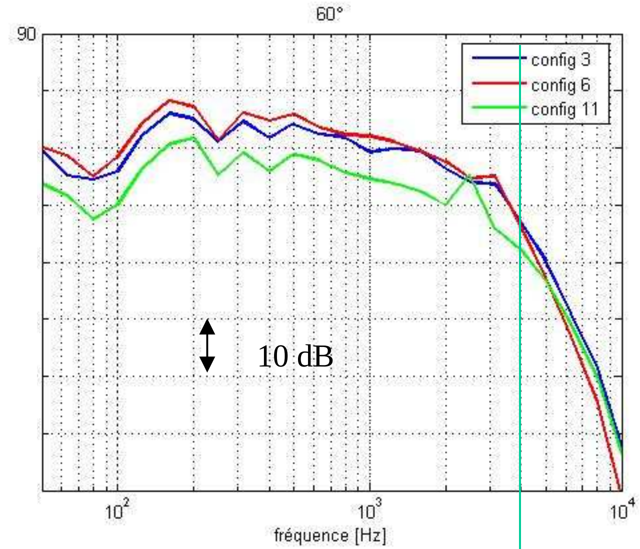
$\Delta\ (1/r) = 1{,}5\ dB$



Inluence of the aircraft configuration on the sound radiated

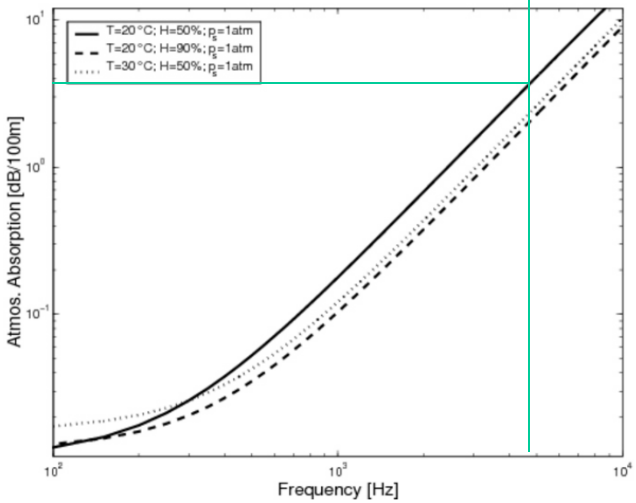
Influence of the engine regime

Flyover	weight	z	regime	v moy
- Conf 3	62.7	*1005*	*90*	*149*
- Conf 6	61.7	*1122*	*95*	*150*
- Conf 11	59.5	*953*	*72.5*	*151*



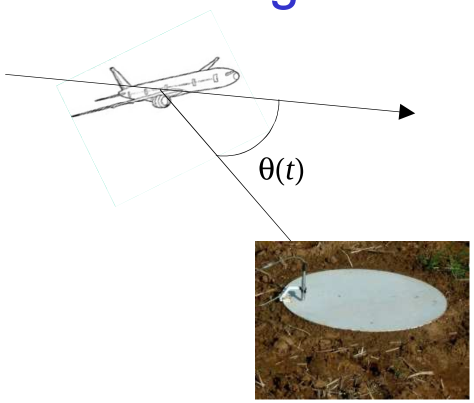
Absorption of sound by the atmosphere

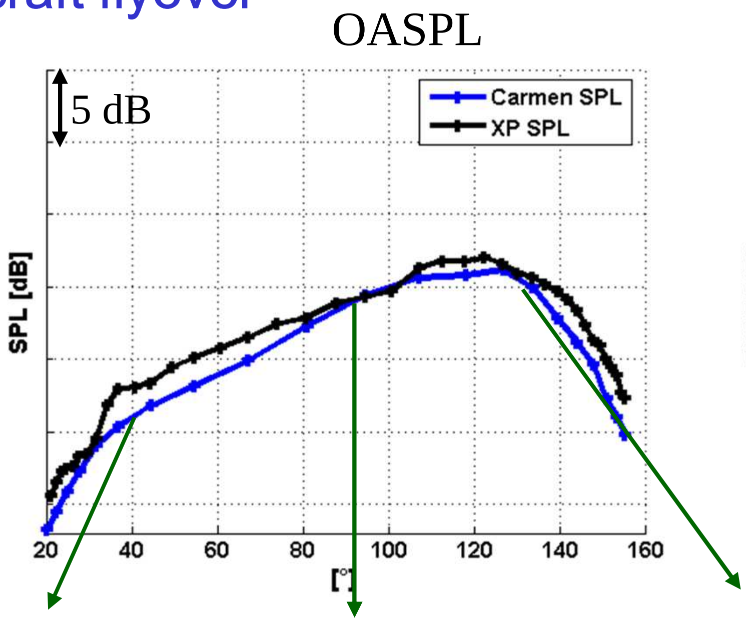
- Atmospheric correction applied according to the ISO norm 9613-1 (Attenuation of sound during propagation outdoors - Part 1: Calculation of the absorption of sound by the atmosphere. ISO 9613-1:1996 Acoustics. 1996)
- H.E. Bass, L.C. Sutherland, A.J. Zuckerwar, D.T. Blackstock, and D.M. Hester. Atmospheric absorption of sound: Further developments. J.A.S.A., 97(1):680–683, 1995.
- Absorption of sound: Further developments. J.A.S.A., 99(2):1259, 1996.

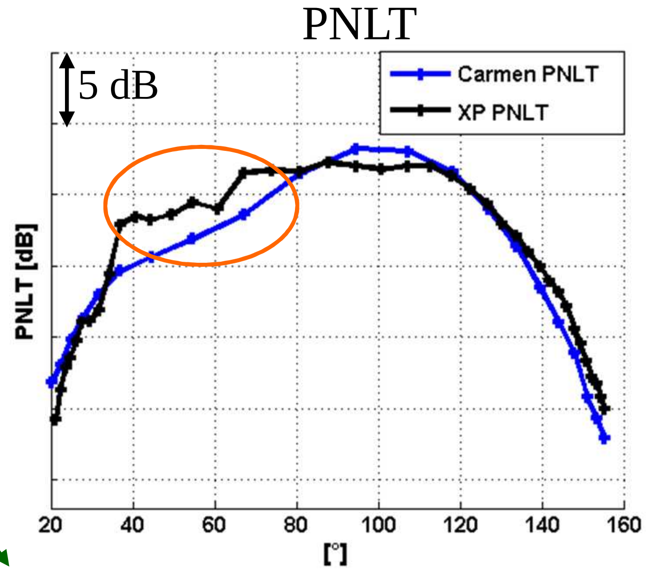


Atmospheric attenuation, dB/100 m

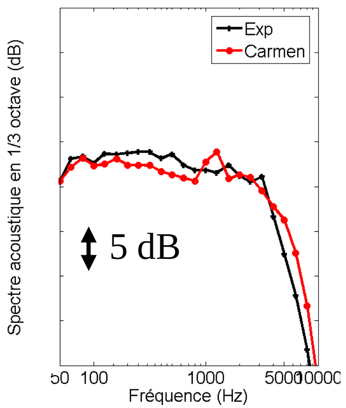
SPL during the aircraft flyover

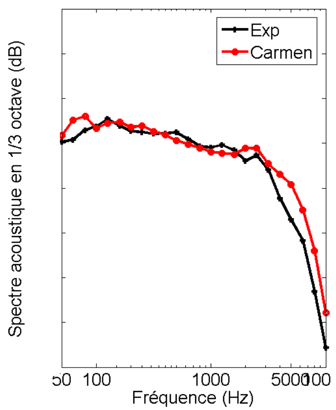


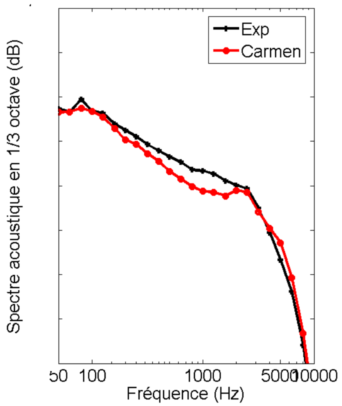




Spectra

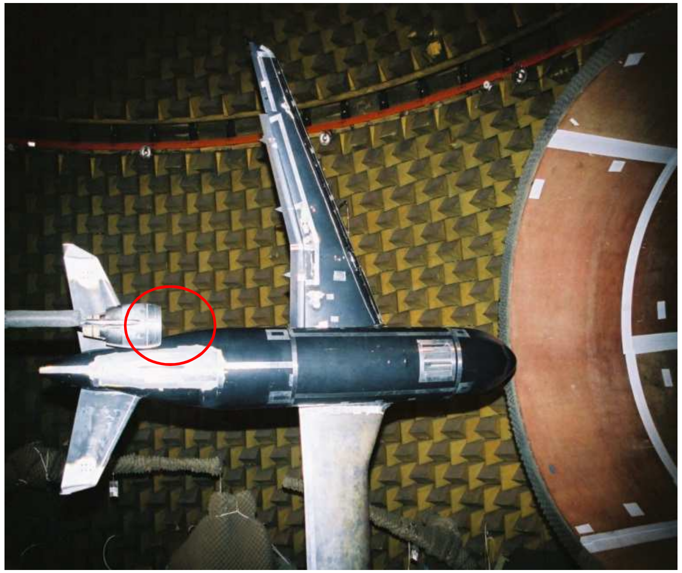




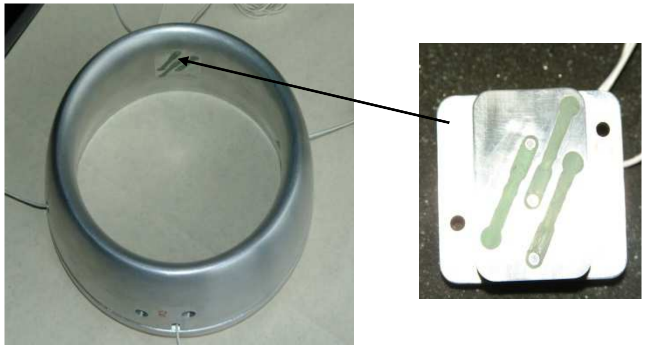


- OASPL and spectra show satisfying results
- PNLT prediction shows up additional deviation

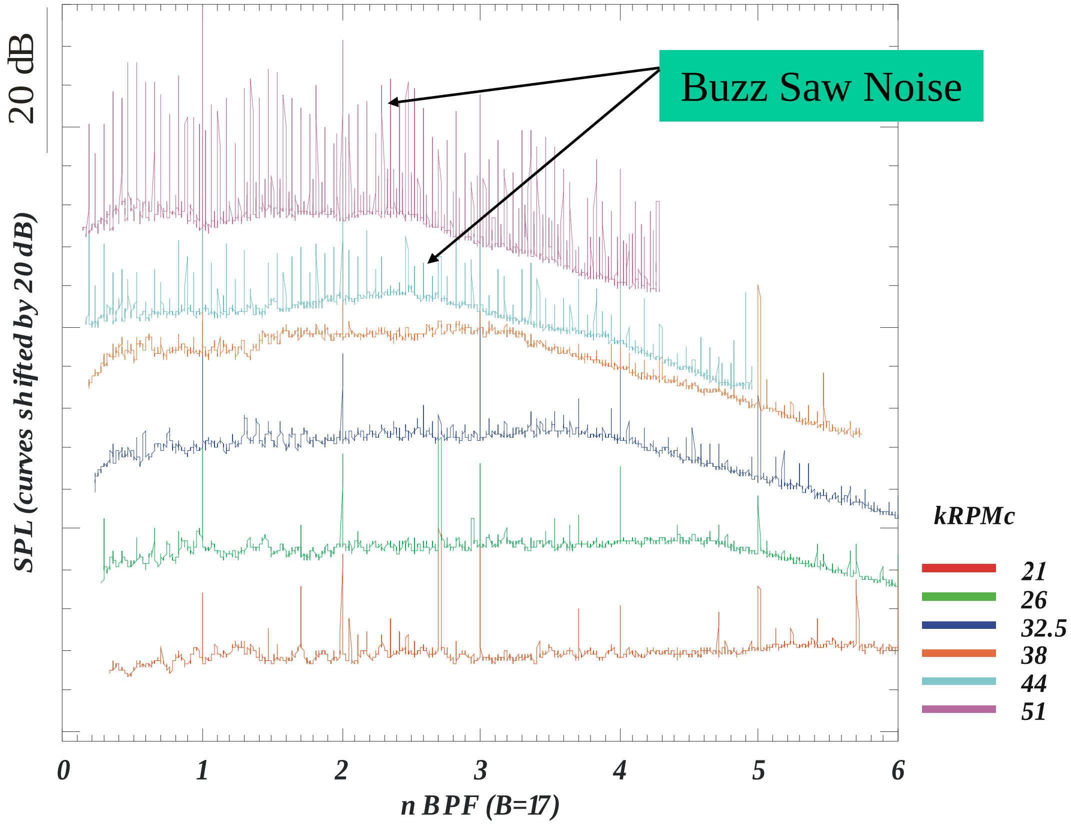
Fan Noise (ROSAS) :
Blade Passing Frequency and Buzz Saw Noise



ROSAS model & TPS nacelle over the fuselage



Kulite instrumenation of the inlet TPS

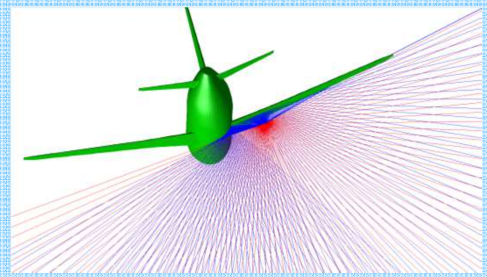


Spectra of the kulite at different RPM

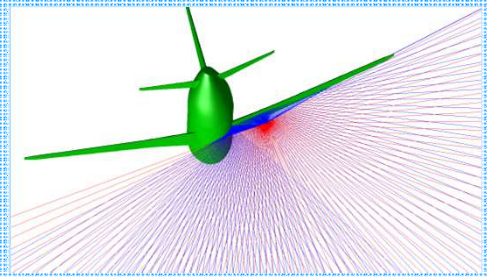
(CARMEN prediction + auralization) and Experiment (PARASOFT Project)

A320 at take-off

Experiment



CARMEN prediction



CARMEN prediction
Buzz Saw Noise increased

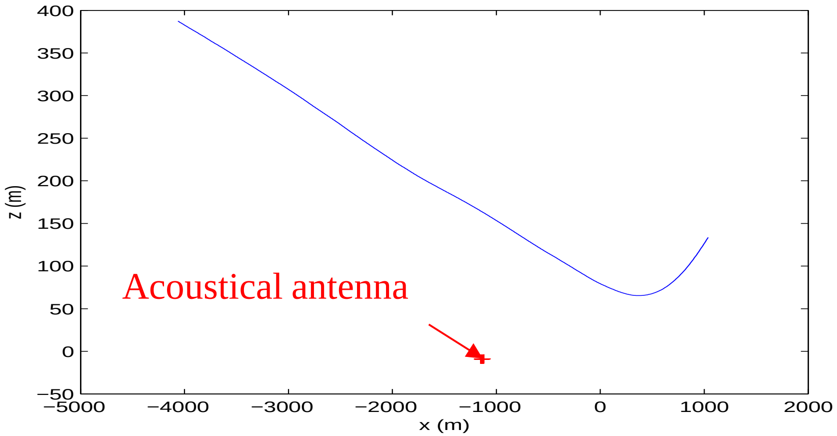
Assessment of CARMEN on a flyover experiment:

A340 during approach

Assessment :
EU-Project AWIATOR

Campaign A340-300 in Tarbes (south of France)

- Experiment dedicated to the noise study of High-Lift-Devices (engine at low speed and landing gear up)
- Flyover at an altitude of 150 m directly above the antenna
- Available inputs : meteorology, aircraft configurations (engine, HLD), signals of the antenna synchronized with the trajectory



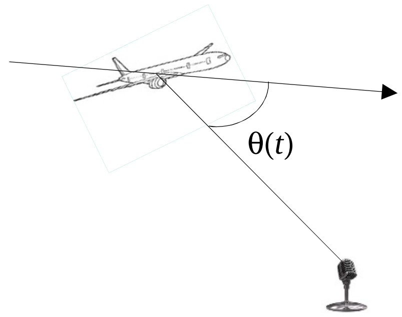
A340 trajectory

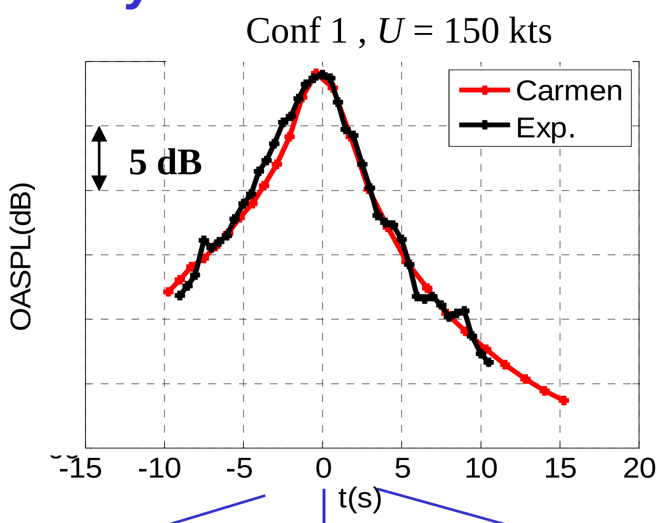
Cross-shape (ONERA) and spiral antenna (DLR) on the ground

Meteorological parameters

- Wind speed and direction, Temperature, Relative humidity measured at 10 meters above the ground
- The AIRBUS meteorological station perform ambient pressure measurements.
- Altitude soundings of relative humidity and temperature carried out during the tests every 45 minutes.
- **The noise measurements are performed under the weather conditions required for noise flight tests: no precipitation, wind less than 12 kts average (15 kts maximum), and cross wind less than 7 kts average (10 kts maximum)**
- The relative humidity and temperature conditions are those of ICAO (Annex 16 Volume 1 second edition 1988)

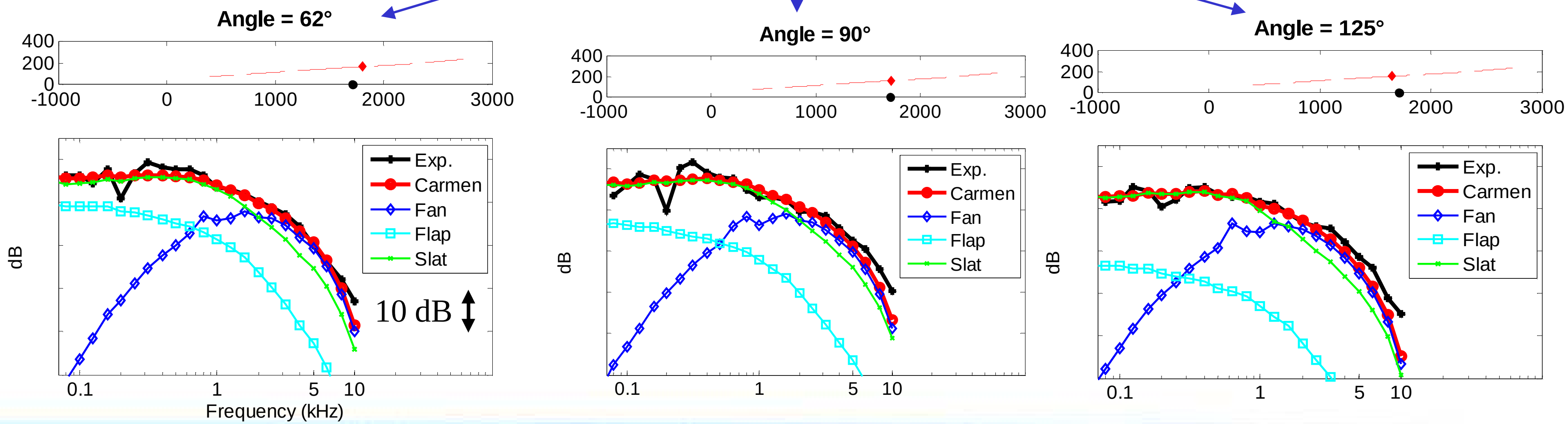
OASPL during the aircraft flyover





- Satisfactory agreement on the OASPL and spectra
- Slat noise dominates

Spectra

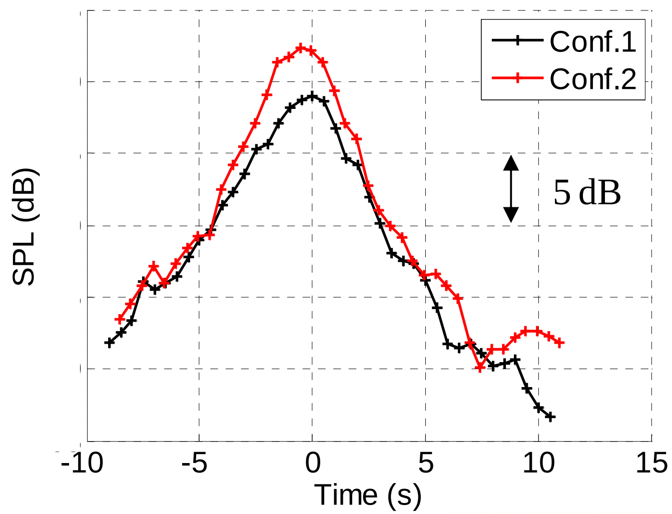


Assessment on 2 aircraft speeds :
CARMEN Prediction / AWIATOR experiment

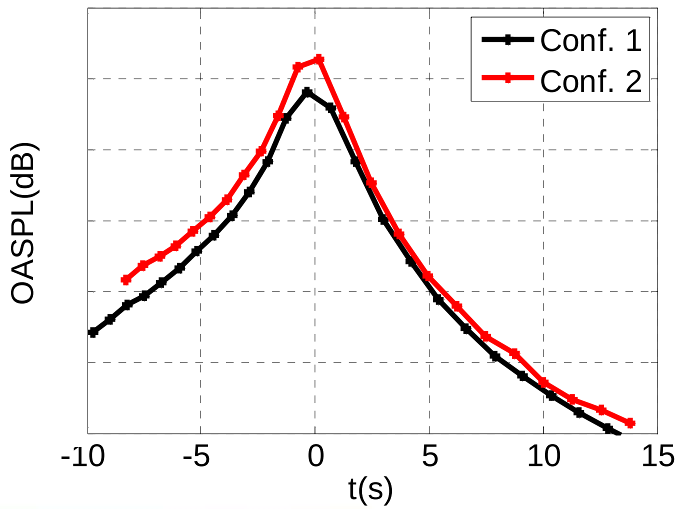
OASPL during the aircraft flyover

Configuration	Speed	Engine regime (low)	steering slat/flap
Conf1	150 kts	30%	23°/26°
Conf2	175 kts	30%	23°/26°

AWIATOR Experiment



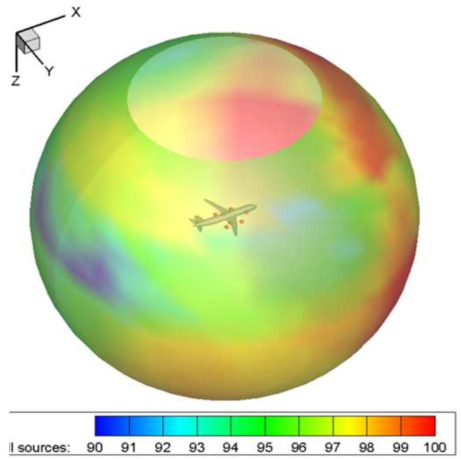
CARMEN-Prediction



Experiment / (CARMEN Prediction + Auralization) (PARASOFT Project)

A340 during an approach phase

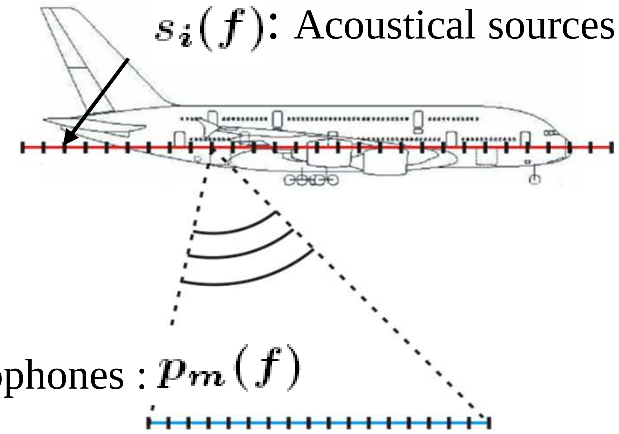
Experiment



Prediction

Microphone phase array to characterize the acoustical sources generated during the A340 Flyover

Principle of DAMAS Moving-Source during flyover



Cross-shape (ONERA) and spiral antenna (DLR) on the ground

DAMAS technique : Deconvoution Algorithm for the Mapping of Acoustic Source [Brooks, *JSV*, 2005], [Fleury & Bulté, *JASA*, 2011]

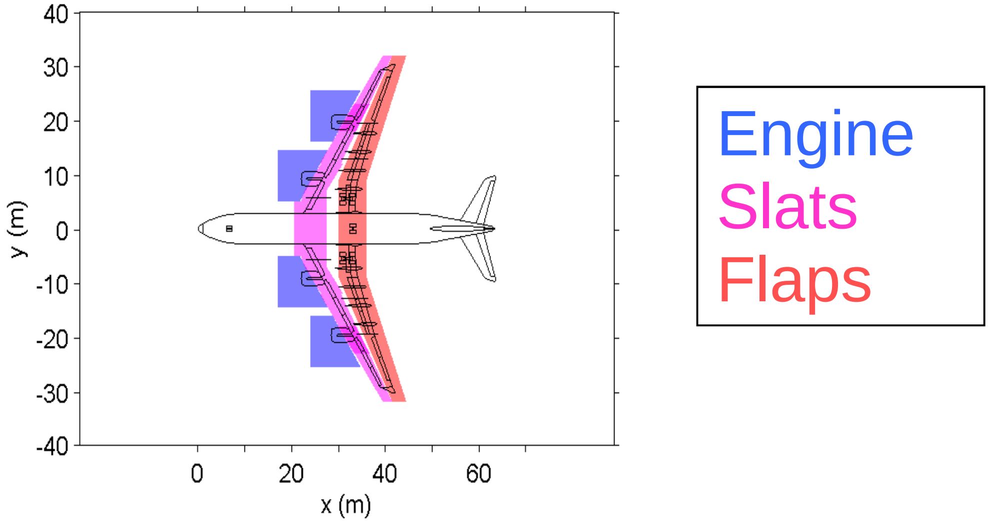
- assumes a set of *a priori* sources on the aircraft
- output *s*: the mean square amplitude of the sources

$Hs = b$, under the constraint $s > 0$

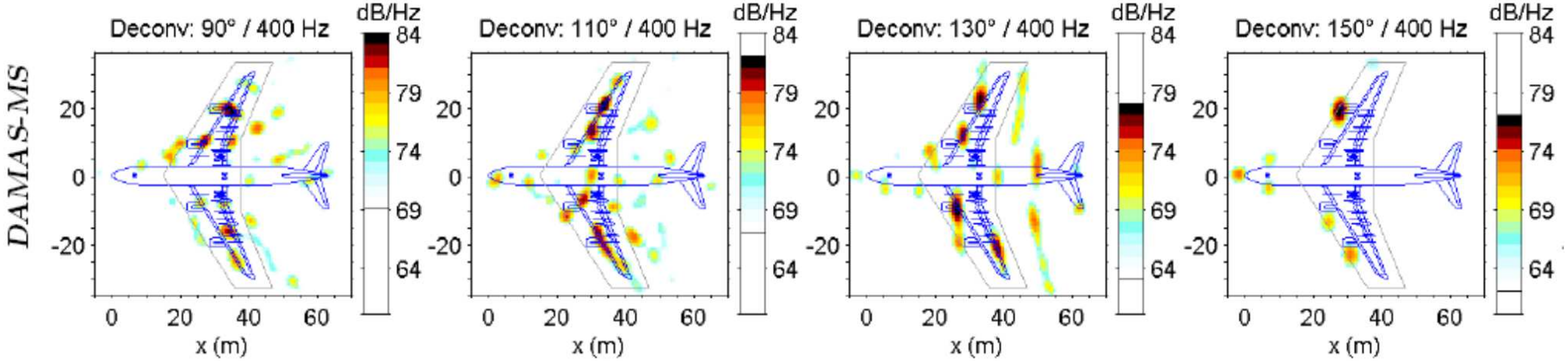
- step 1: b derived from the beamforming: $b_i = \sum_{m,n=1}^{N_M} G_{i,m}^* \Gamma_{m,n} G_{i,n}$
- step 2: $H_{i,j} = \left|K_{i,j}\right|^2 \quad K_{i,j} = \sum_{m=1}^{N_M} G_{i,m}^* G_{j,m}$

DAMAS-MS applied to A340 during approach

Decomposition into acoustical source zones of the A340



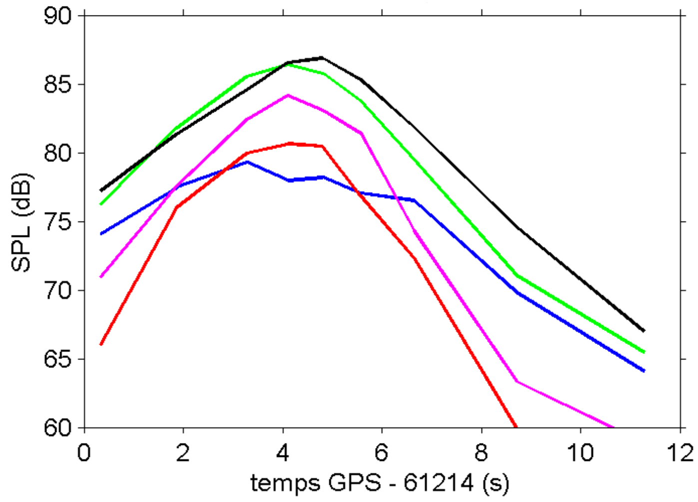
Mapping of the sources on the aircraft at several locations, f = 400 Hz



Overall Sound Pressure Level of each source during flyover
Measurement / DAMAS estimation

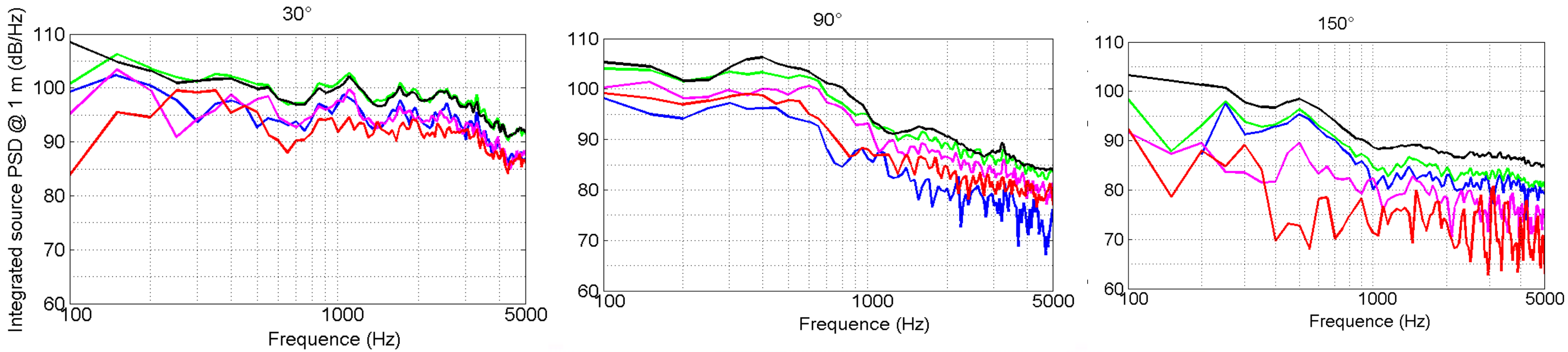
OASPL

[V. Fleury, P. Malbéqui, AIAA *J.* 2013]



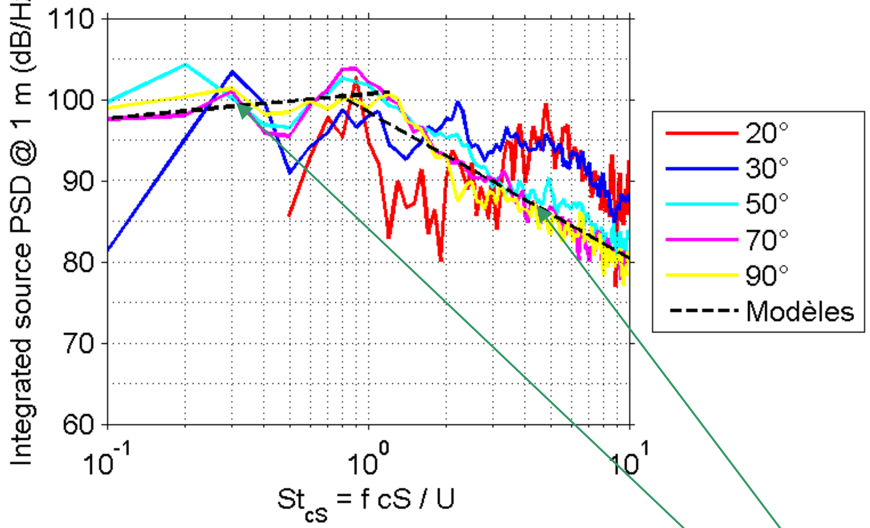
- Engine
- Slat
- Flap
- Total DAMAS
- Total Measurement

Spectra

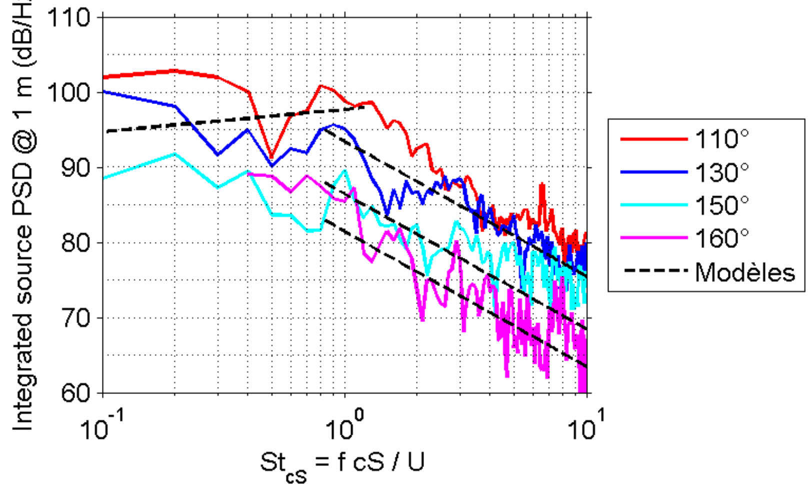


Slat Noise:
DAMAS technique / Dobrzynski modelling

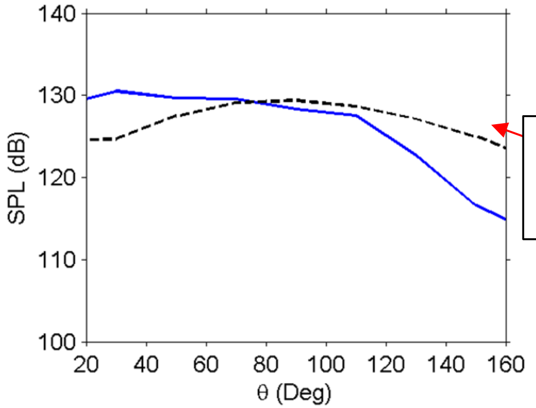
Spectra upward



Spectra downstream



Directivity

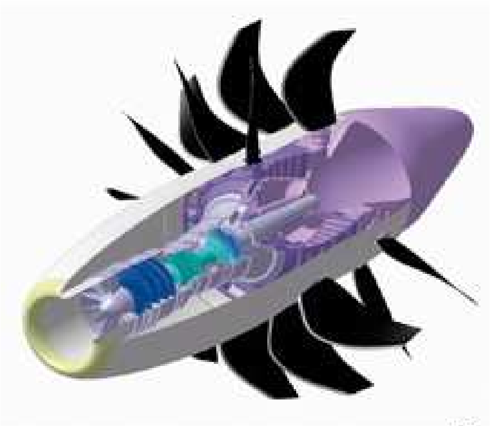


Dobrinzynski
DAMAS

[Dobrzynski *& al., AIAA Paper 2001-2158*]

- $St^{-1,8}$
- $St^{0,3}$
- wing chord: cS = 15 cm
- wing slat angle: δS = 23°
- $\sin(\theta-\delta S)^2 + 0{,}1\cos(\theta-\delta S)^2/(1-M\cos\theta)^4$

Prediction of the contra-rotative propeller (CROR)



DR

Contra-Rotative Open Rotor - CROR

Context

- CROR reduces the fuel consumption compared conventional single propfans.
- CROR can motorize mid-distance aircraft at cruise Mach number of 0.7 to 0.8.
- Extensively studied in the 80s to power aircraft and since last years

CROR mounted on a McDonnell-Douglas MD-80

Acoustic issue

- Noise generated by the two isolated rotors + **interactions between the two blade rows**.
- Noise radiates freely ≠ ducted engines: i) the nacelle acts as a noise guide ii) allows acoustic liners implementation

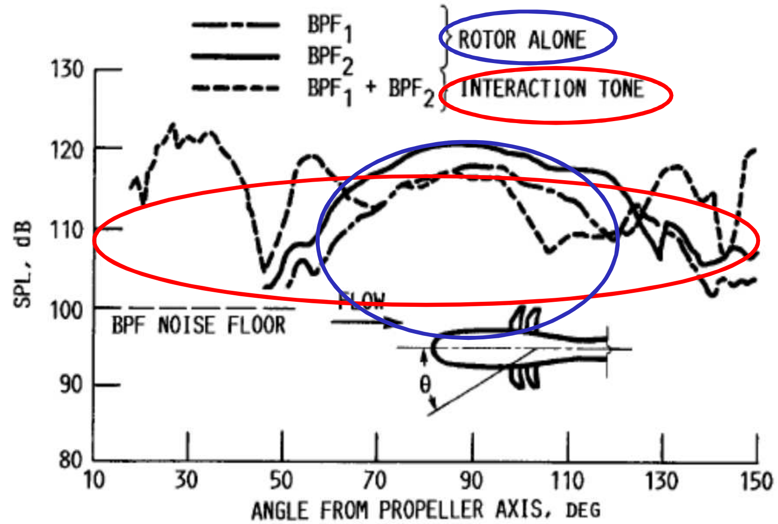
The Contra-Rotating Open Rotor model

Tone noise

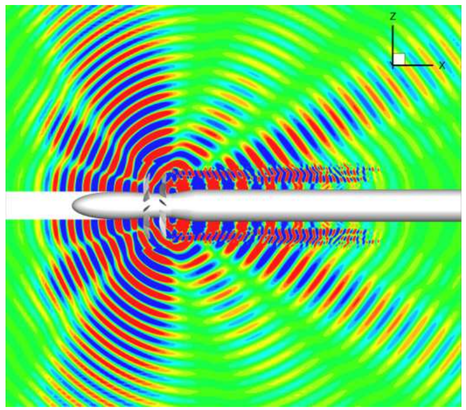
- Repartition of the loads along the blade wingspan [Hanson, 1985].
- Tones due to each rotor efficiently radiate at cruise.
- Interaction tones $f_{12} = (n_2B_2+n_1B_1)\ \Omega$ occuring at low circumferential mode $m = n_2B_2- n_1B_1$ **strongly radiate near the centerline** due to the mth low-order Bessel functions behavior.

Broadband noise

- Semi-analytical model provided [Blandeau, 2011].
- Self-noise of the blade profile located at the trailing edge, radiating for the two rotors.
- Interaction noise of the turbulence with the blade



[Woodward, AIAA Paper 1987]

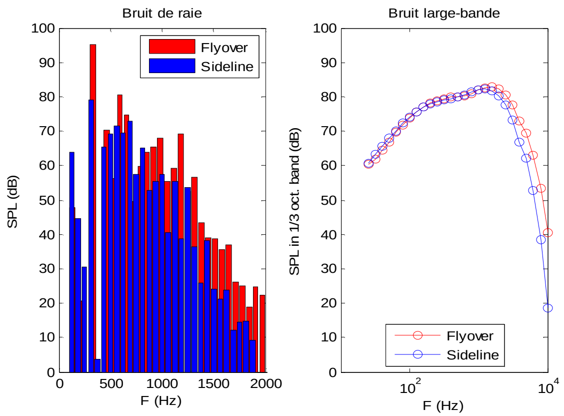


[Chelius, Le Garrec, Mincu, AIAA Paper 2015]

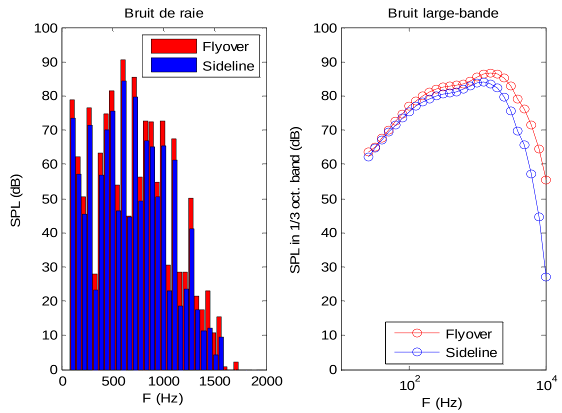
Contra-Rotating Open Rotor simulations with CARMEN

CROR simulations

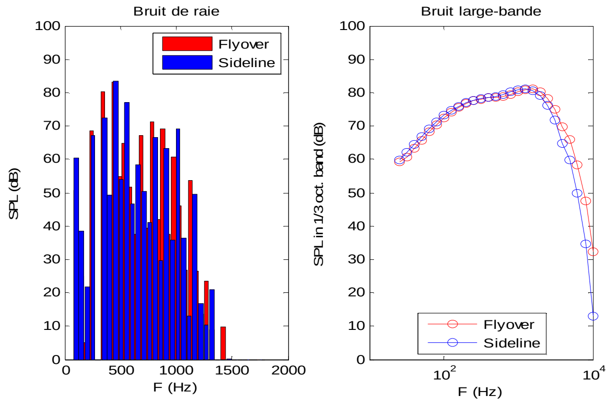
- Mid-distance aircraft type motorized with two CRORs
- Standard take-off trajectory with a rising slope of 5.5° from altitude 200 to 300 m



a) Aircraft approaching the flyover point (t = 7 s)



b) Aircraft directly above the flyover point (t = 11.5 s)



c) Aircraft moving away from the flyover point (t = 16 s).

CARMEN prediction of the time variyng spectra & sound synthesis

Mid-distance aircraft type motorized with two CRORs at take-off

Microphone

CRORs with 12x8 blades [from IESTA-CARMEN Platform]

CARMEN prediction of the time variyng spectra & sound synthesis

Mid-distance aircraft type motorized with two CRORs at take-off

Microphone

CRORs with 2 different sets of blades [from IESTA-CARMEN Platform]
Alternating 12 x 8 (red)   vs.   12 x 13 (jaune)

LABEX CELYA
ONERA

Summary

- Accurate prediction is necessary to reduce the noise level, perception and annoyance studies are also pertinent to “design” the aircraft noise.
- CARMEN predicts the acoustical footprints of an aircraft, providing realistic data for impact noise studies on new concepts, including shielding effects, to lower the sound level.
- Existing acoustical sources, such as: jet noise, fan, flap, slat, landing gear, etc. are accurately predicted thanks to semi-empirical models tuned with WT experiments.
- The a/c prediction is limited for new concepts when the source modelling is not available

Thanks to:

- *My ONERA’s colleagues: S. Aubry, J. Bulté, R. Davy, I. Legriffon, L. Sanders,*
- *Airbus-France for providing SILENCER and AWIATOR results*
- *Genesis for synthesing the CARMEN predictions (PARASOFT project)*

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- S. Léwy, *Semi-empirical prediction of tone noise due to counter-rotating open rotors*, Proceeding of the 20th International Congress on Acoustics, Sydney, Australia, 23-27 August, 2010.
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Modelling and assessment (2/2)

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- I. Le Griffon, P. Malbéqui, *Physical modelling and assessment methodology of aircraft noise prediction in IESTA*, Aéro-Tech SAE, Toulouse, octobre 2011.
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