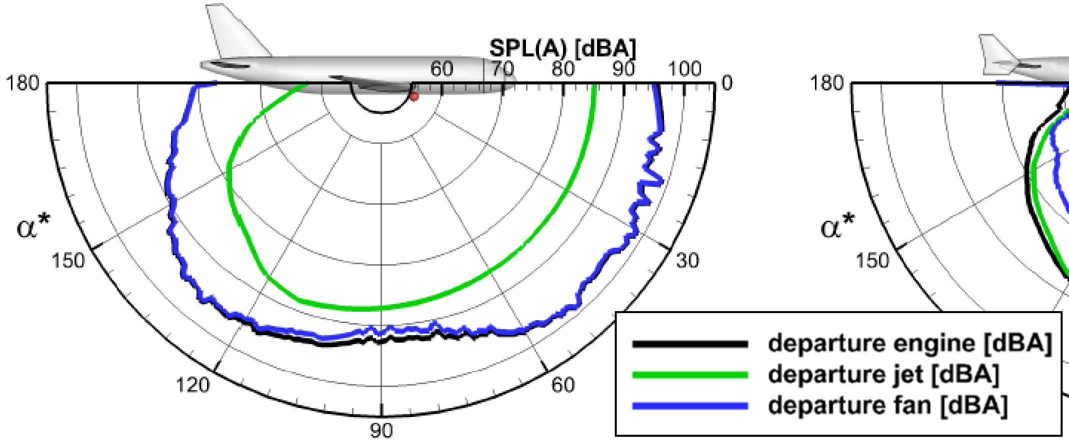
22nd CEAS-ASC Workshop 2018: *Future Aircraft Design and Noise Impact*, Amsterdam

10 years of joint research at DLR and TU Braunschweig toward low-noise aircraft design – what did we achieve?



Lothar Bertsch[1],
Wolfgang Heinze[2], Sébastien Guérin[1], and Markus Lummer[1]
[1] DLR, [2] TU Braunschweig

DLR

Technische Universität Braunschweig

presentation outline

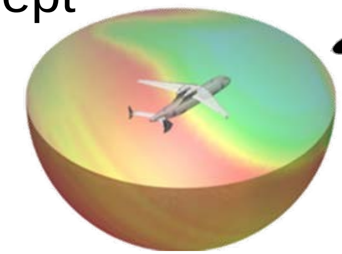
- introduction
- motivation
- development
- application
- summary & outlook

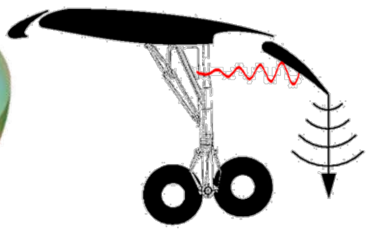
introduction: influence of aircraft design on noise

working hypothesis: design constraints define acoustic performance

examples:

- TLAR → weights, wing design, propulsion concept





- vehicle layout → installation & interaction effects
- aerodynamics → flow velocities & high-lift concept / usage

$I_{airframe} \sim {v_{local}}^5$

- engine thrust (e.g. turbofan) → rotational speed, jet speeds

$I_{jet} \sim {v_{jet}}^{7-8}$

$I_{fan} \sim {v_{fan}}^{5-6}$

- takeoff/landing performance → glide slope/ground distance Δh, velocities, high-lift, exposure times

$I_{total} \sim \Delta h^2$

- landing gear → installation, size

$I_{gear} \sim {v_{lokal}}^6$

introduction: low-noise aircraft design

status quo before cooperation:

- DLR & TU Braunschweig: a/c noise & design as **separate** disciplines

- previous, more **comprehensive** research initiatives:
    - Quiet Aircraft Technology (QAT) program, 1999, NASA
    - Silent Aircraft Initiative, 2003, Cambridge and MIT

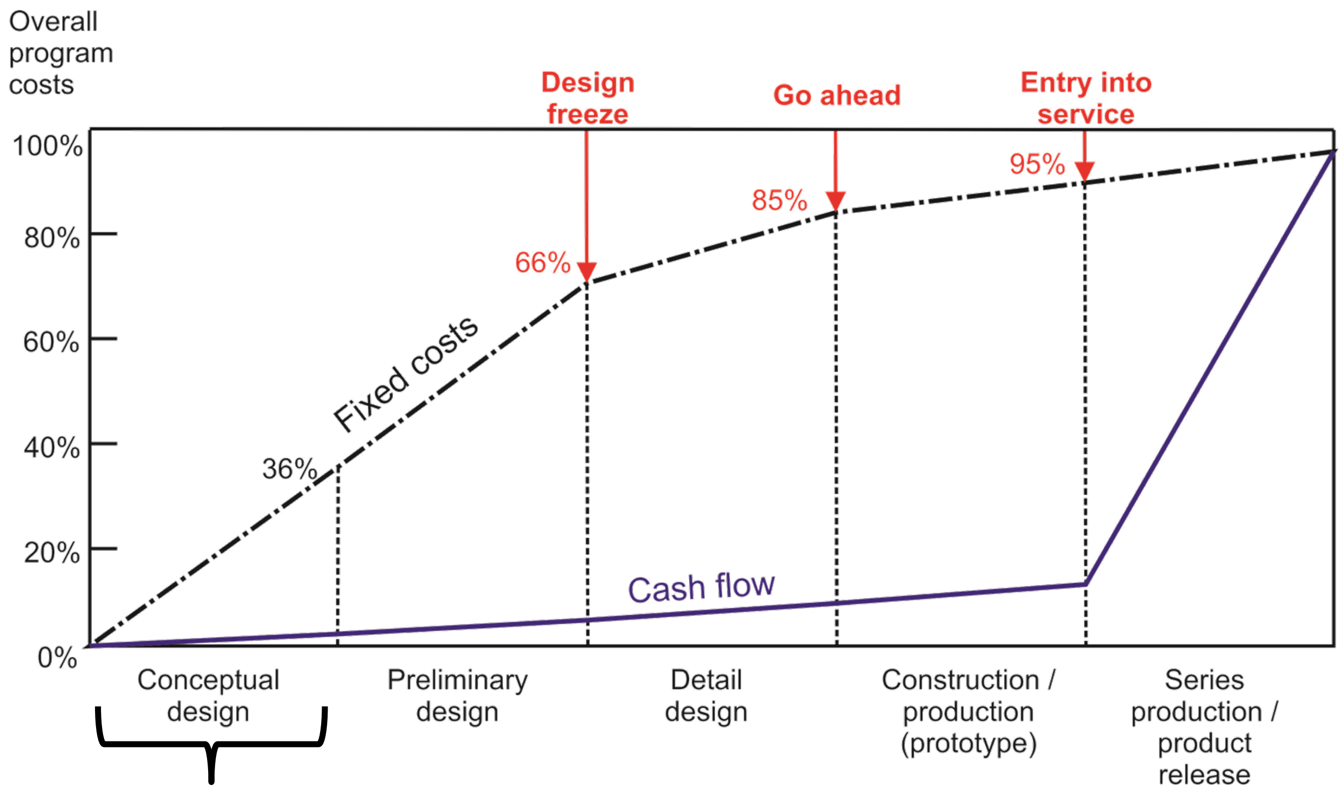
- disadvantages found in available literature:
    1. acoustics not available within overall a/c design phase → subsequent noise assessment of predefined concepts
       (limited solution space: no design variation/optimization)
    2. incomplete consideration of relevant disciplines/interactions
    3. insufficient problem assessment
       (focus limited to: emission situation, a/c components, specific noise metric, and/or fixed operating conditions)

presentation outline

- introduction
- **motivation**
- development
- application
- summary & outlook

motivation

main objective: **exploit** noise reduction **potential** by a/c design



- reduced complexity but all relevant disciplines are considered (global assessment)
- large solution space (few limitations)
- direct comparability of stronly varying a/c concepts

consequence: assess and intervene **within conceptual design**

graph © W. Heinze, TU Braunschweig

motivation

launch joint research with TU Braunschweig in 2008:
low-noise aircraft design

- join forces (tools/methods/data/expertise):
    - DLR: flight simulation, engine design, and a/c noise assessment
    - TU BS: a/c design process
- develop comprehensive noise prediction code
    - simultaneous consideration of design *AND* operation
    - overall a/c and componential assessment (noise source breakdown)
    - problem assessment: (1) multiple noise metrics, (2) varying operating conditions along realistic flights, (3) multiple observer locations
- improve a/c design process
    - provide required input for noise assessment
    - noise as a design objective

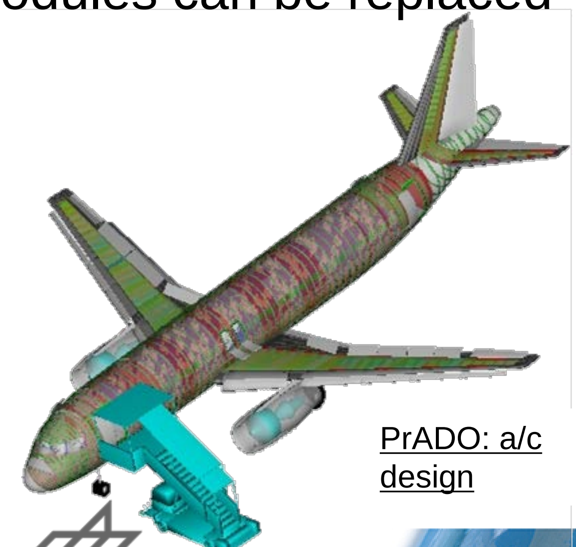
presentation outline

- introduction
- motivation
- development (selected milestones)
    - 2008 – „bringing the disciplines together“
    - 2012 – „fully automated low-noise design process“
    - 2017 – „focus on noise immission“
- application
- summary & outlook

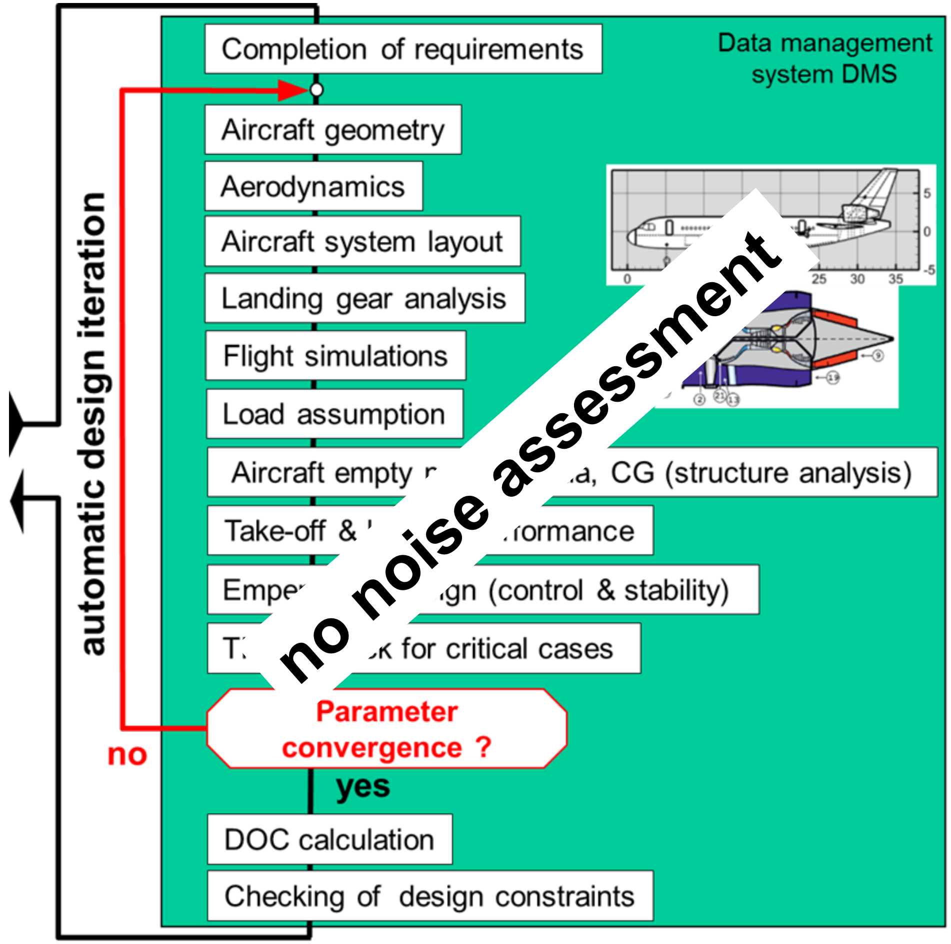
2008: bringing the disciplines together

<u>status quo at TU Braunschweig:</u>
Preliminary Aircraft Design and Optimisation (**PrADO**)

- aircraft design synthesis
- iterative & multidisciplinary
- common data base
- individual modules for defined tasks
- modules can be replaced



<u>PrADO: a/c design</u>



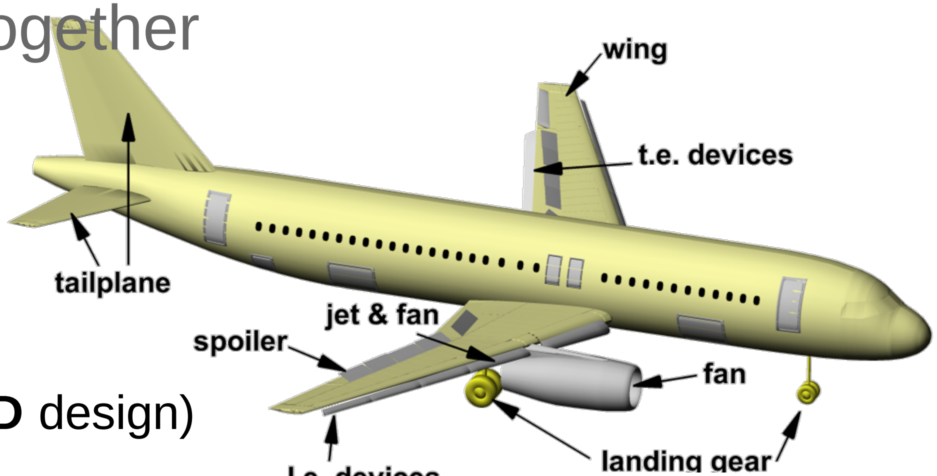
<u>PrADO: process</u>

Ref.: Heinze, ZLR-Forschungsbericht, 1994

2008: bringing the disciplines together

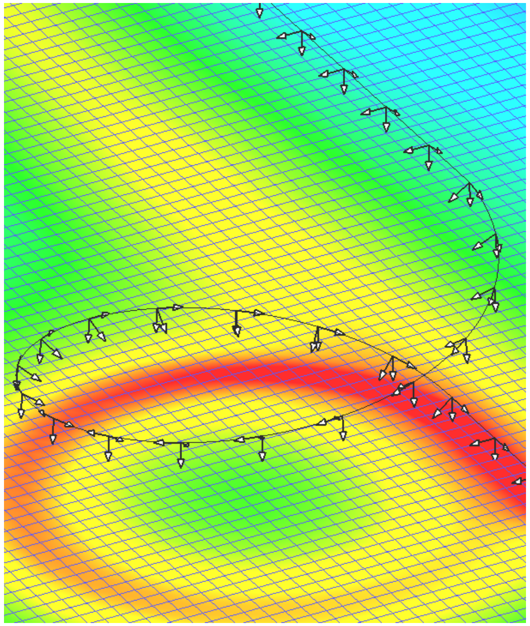
<u>new prediction tool at DLR:</u>

Parametric Aircraft Noise Analysis Module (**PANAM**)



<u>PANAM noise sources</u>

- parametric description (operation **AND** design)
- combine individual noise sources
  - airframe: Dobrzynski
  - engine: Heidmann/Kontos & Stone
- modular setup (implement new models/interfaces)
- adequate complexity & input requirements
  - a/c design (**PrADO**)
  - engine design / performance deck (Hi-Fi sim.)
  - flight trajectory (FDR, flight simulator)
- output data:
  - std. metrics (SPL, PNL, EPNL, SEL)
  - arbitrary observers (single, array)


<u>PANAM output: isocontour area</u>

2008: bringing the disciplines together

input data

aircraft geometry/layout (integration of new technology)
PrADO

detailed flight trajectory (including high-lift and gear)
flight simulator or FDR

engine thermodynamic cycle and geometry
external sim. data (VarCycle)

noise prediction

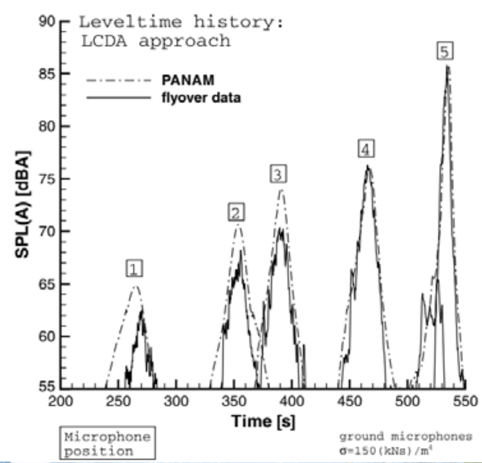
parametric & componential noise source models

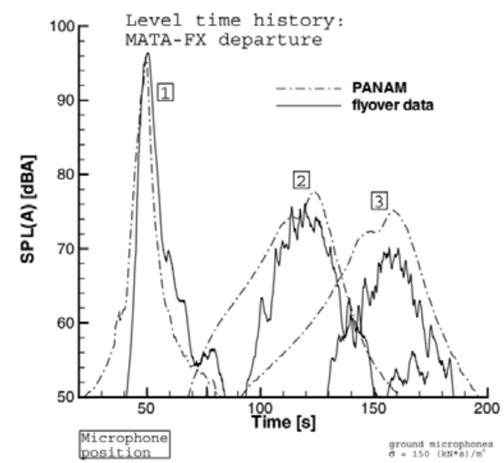
classical noise sources:
- airframe (clean, flap, slat, spoiler, gear) & engine (jet, fan)

PANAM (updated)

verification / validation example

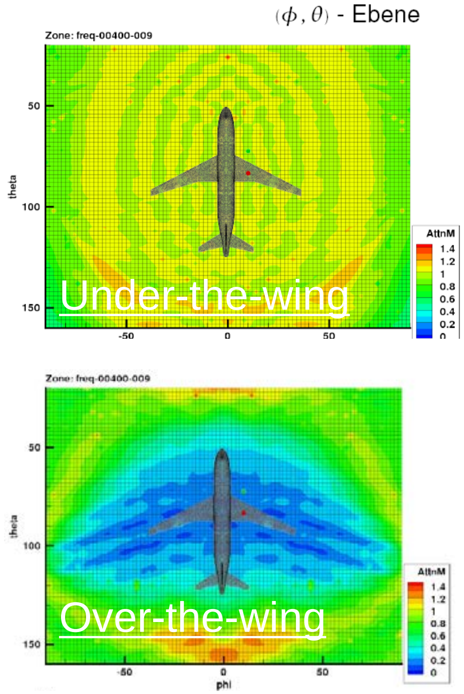
- reference vehicle A319-100
- FDR as input (N1, TAS, flaps …)
- 18 flights: 9 approach @ 13 mics;
  9 departure @ 12 mics
- satisfying agreement with exp. data





2012: fully automated low-noise design process

<u>process is updated:</u> DLR tool SHADOW
- ray-tracing with diffraction correction (Maggi-Rubinowicz)
- input: PrADO 3D aircraft geometry (incl. engine position)
- output: shielding factor (ΔdB / frequency band)
    - applied to PANAM noise source prediction



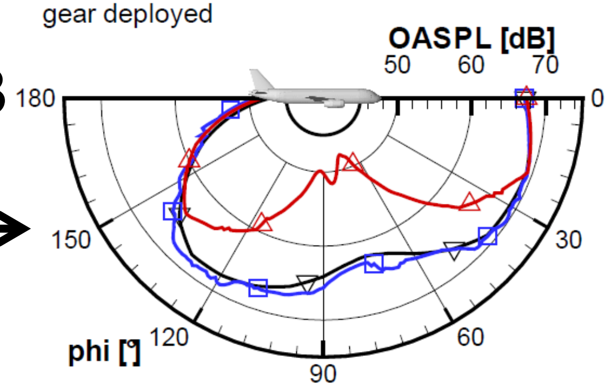
ΔdB

FAN noise directivity*

Legend:

Operating condition:
TAS [m/s] = 70.0
Thrust [kN] = 10.0
flaps [°] = 40.0
slats [°] = 27.0
gear deployed

Component:
panam
panam & shadow
over-the-wing



*) overall SPL on reference sphere (r=80m)

Ref.: Lummer, AIAA 2008-3050

2012: fully automated low-noise design process

input data

- aircraft geometry/layout (integration of new technology)
- detailed flight trajectory (including high-lift and gear)
- engine thermodynamic cycle and geometry

PrADO (updated)

optionally: external input data (PANAM interface)

noise prediction

- parametric & componential noise source models
- classical noise sources: - airframe & engine
- automated airframe segmentation (required for complex wing/tailplane designs, e.g. fwd and bwd sweep)
- acoustic fan noise lining (bypass & core, broadband & tonal)

PANAM (updated)

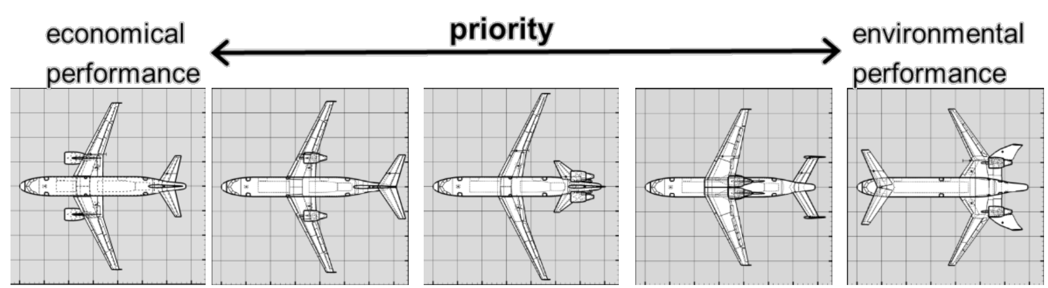
- acoustic installation effects (here: applied to fan noise)

SHADOW

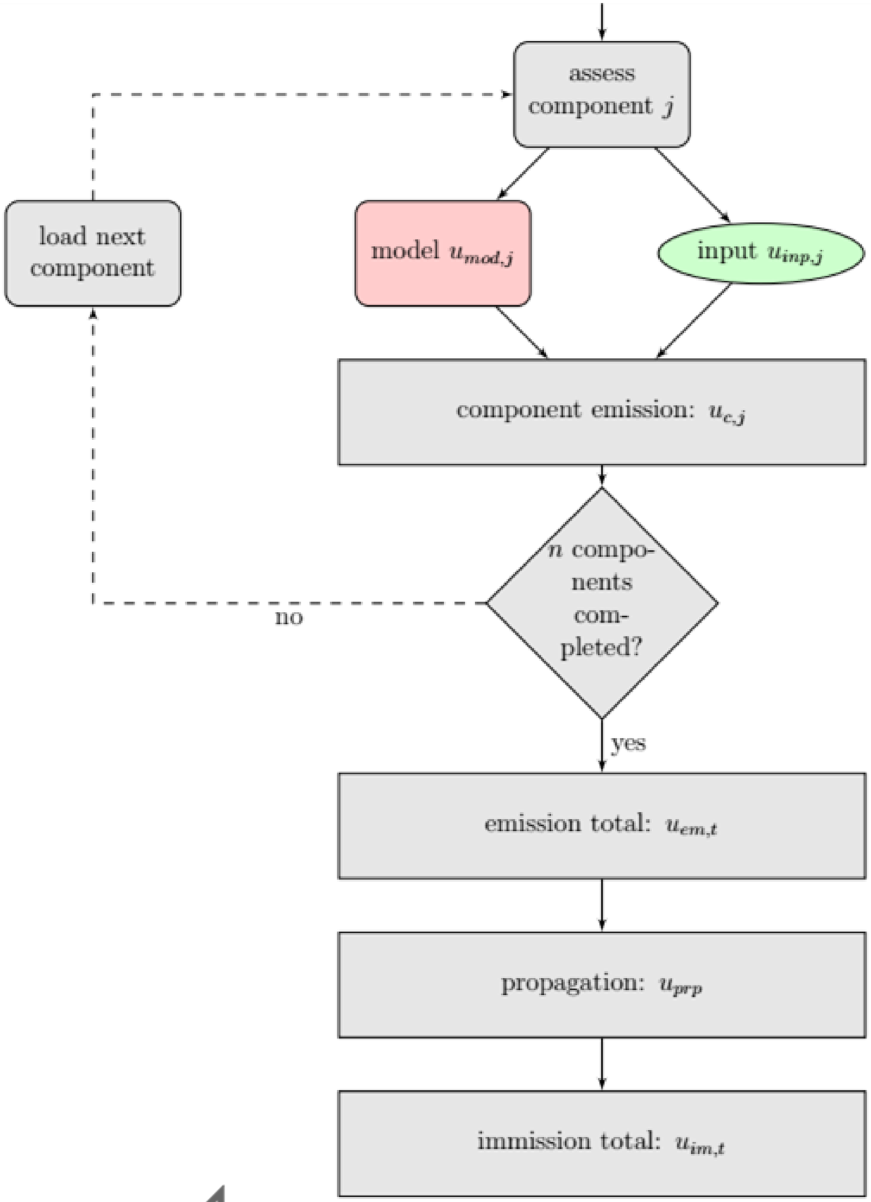
PrADO: input data generation for PANAM

proof of concept

- noise as a design constraint
- study with **500** a/c design variants
- assessment along simulated and predefined flight procedure



2017: focus on noise immission



<u>PANAM is updated:</u>
uncertainty assessment

$$u_{c,j} = \sqrt{u_{mod,j}^2 + u_{inp,j}^2}$$

$u_{inp,j}$: input parameters and their uncertainties
$u_{mod,j}$: applied noise source model

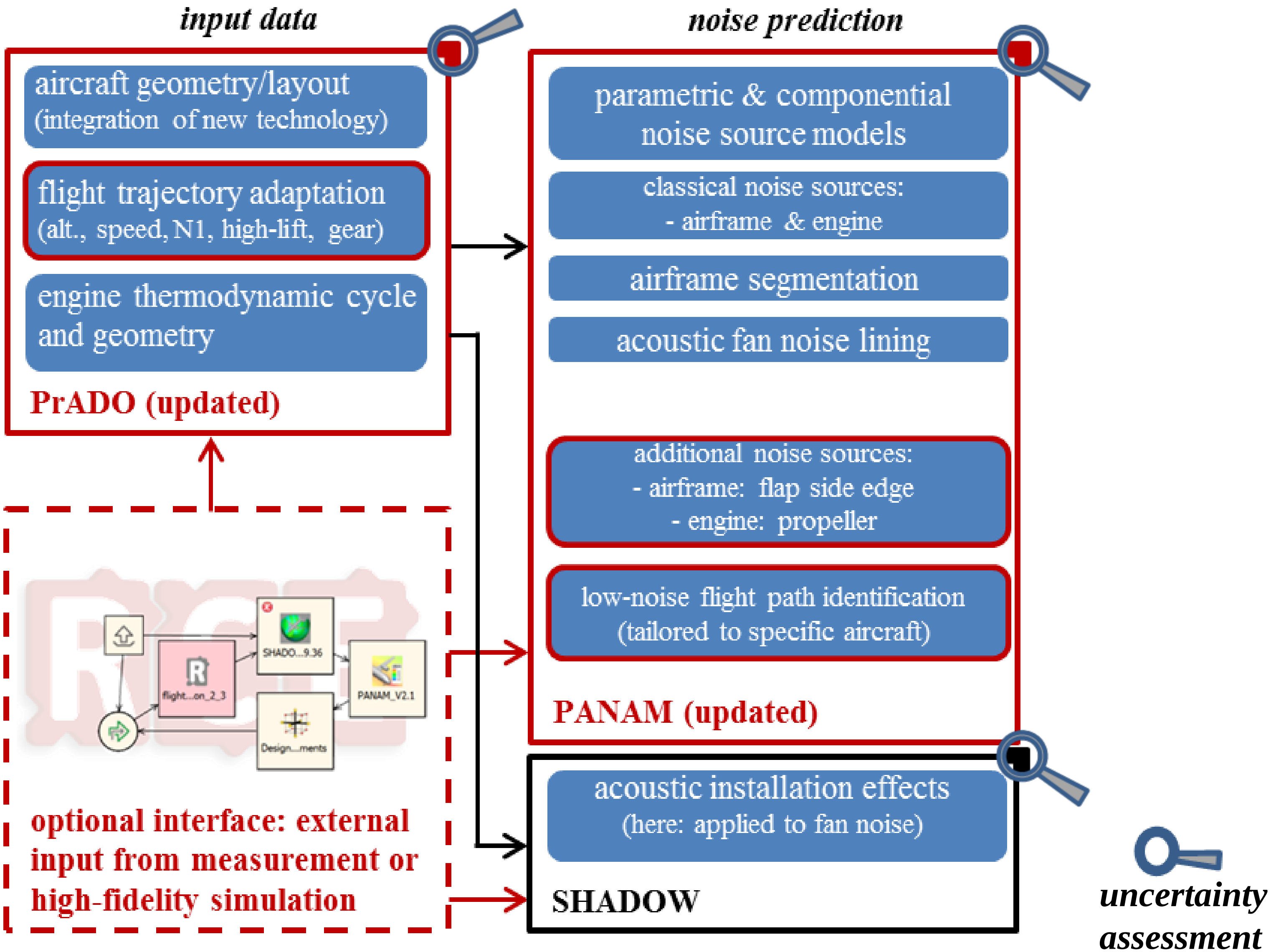
energetic weighting of components

$$u_{em,t} = \sqrt{\frac{\sum_{j=1}^{n} \left(u_{c,j} \cdot 10^{L_{em,j}/10}\right)^2}{\sum_{j=1}^{n} \left(10^{L_{em,j}/10}\right)^2}}$$

total uncertainty of predicted immission

$$u_{im,t} = \sqrt{u_{em,t}^2 + u_{prp}^2}$$

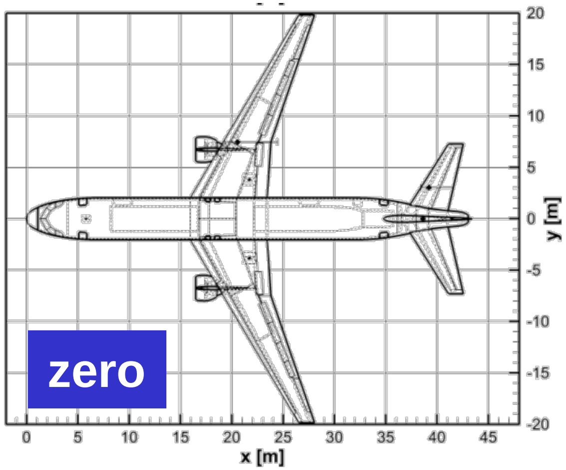
2017: focus on noise immission



presentation outline

- introduction
- motivation
- development
- application
- summary & outlook

application
2017 study*



<u>tube-and-wing a/c design:</u>
- top level aircraft requirements (TLAR)
  - 4000 km range
  - 180 Pax
  - 1890 kg payload
  - cruise Mach 0.8
- reference: “zero” w. **BPR 6** engines

<u>low-noise design modifications:</u>
- engine: replacement with geared turbofan (**BPR 12**)
- architecture: engine noise shielding concept**
- airframe: low-noise high-lift and gear concept

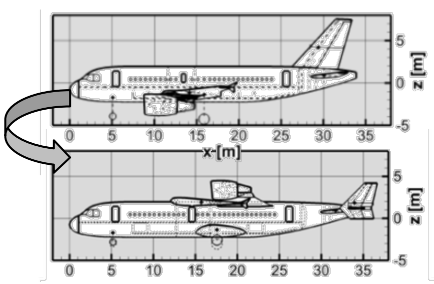
<u>presentation today:</u>
effect of engine replacement (on conventional and on low-noise a/c)

*) AIAA 2018-0264, Bertsch et al. **) TLAR: cruise Mach of 0.7

application: vehicle concepts / technologies

	conventional		low-noise	
	zero	**neodapt**	**V-2 (af)**	**fanex**
engine	ref	GTF	ref	GTF
architecture	ref	adapted	fan shielding	fan shielding & adapted
airframe	ref	ref	low-noise	low-noise

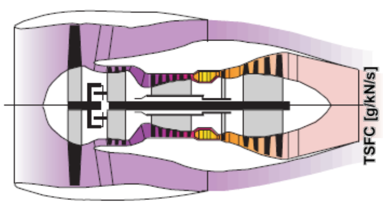
<u>fan shielding</u>



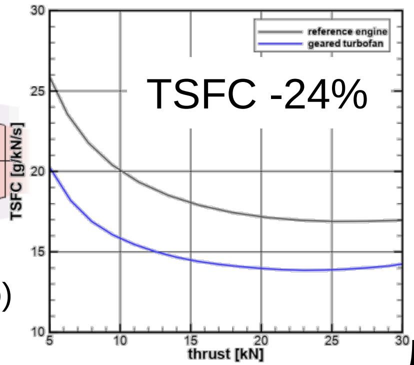
selected fan shielding

based on large design study (2013)

<u>GTF (BPR 12)</u>

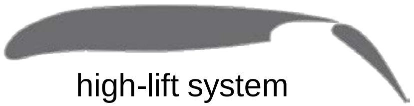


GTF (left fig. © GasTurb)



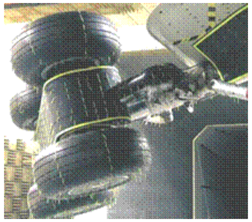
external high-fidelity simulation → design, weight, performance

<u>low-noise airframe:</u>



high-lift system

external exp. / simulation → weight, aerodynamics, ΔdB



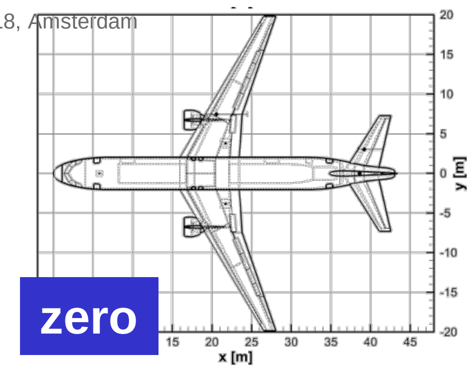
gear mesh fairing
(fig. © Dobrzynski)

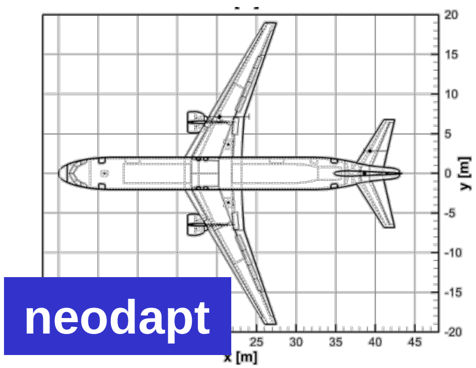
previous findings → ΔdB

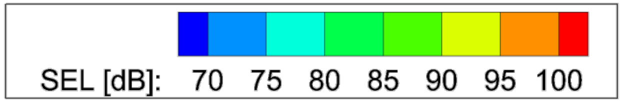
low-noise airframe: gear *–3dB*, slats *–6dB*, flaps *–5dB*

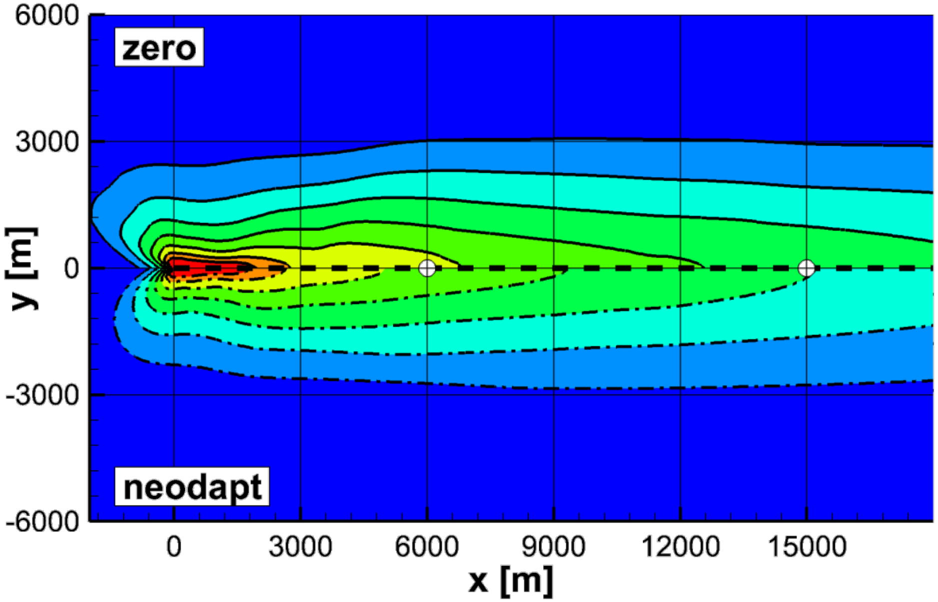
application

engine replacement
on reference architecture





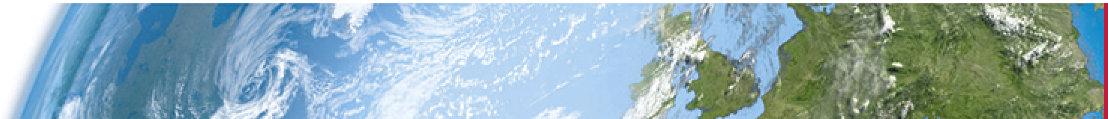




metric	Δ (neodapt-zero)	
	6 000 m	15 000 m
$L_{A,max}$ [dB]	**-3.5**	**-4.9**
$EPNL$ [dB]	**-6.2**	**-5.8**
SEL [dB]	**-3.1**	**-3.1**

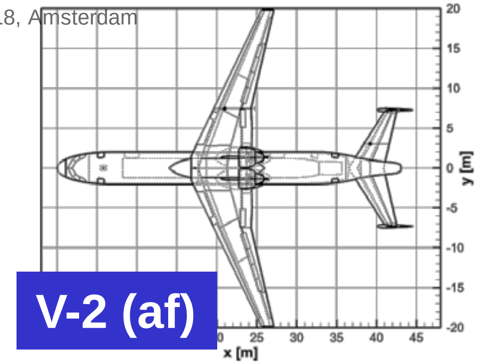
DOC [€/flight]	**-1452** (-7.75%)

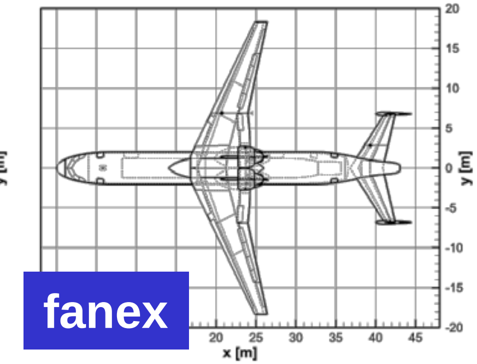
- gtf reduces noise levels (jet → $L_{A,max}$ & SEL, fan → $EPNL$)
- significantly reduced Direct Operating Costs (per flight)

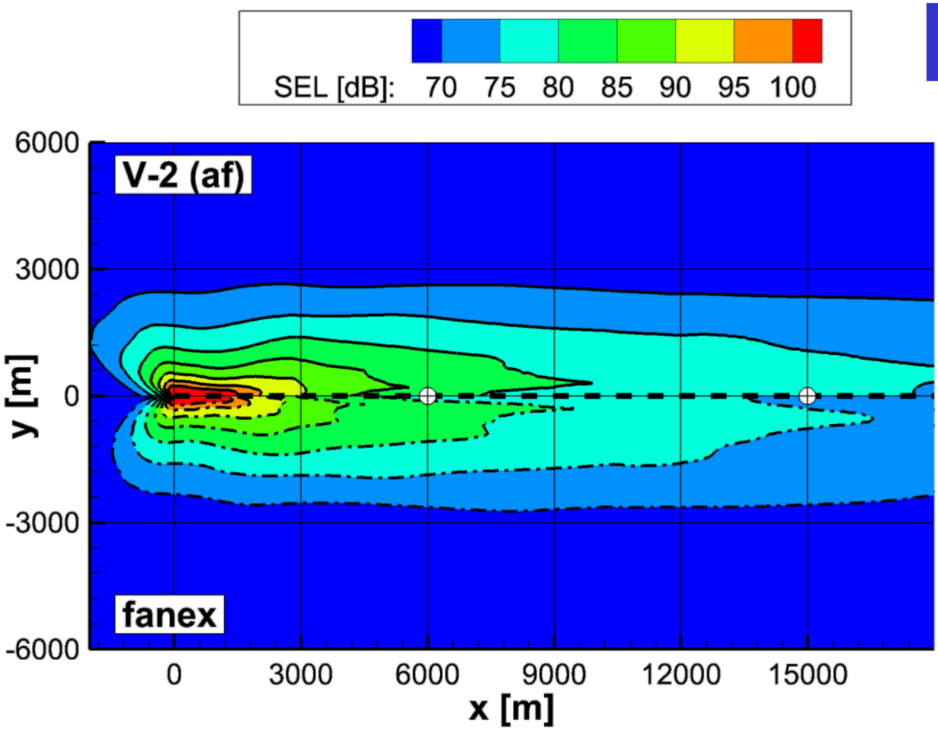


application

engine replacement
on shielded architecture







metric	Δ (fanex – V-2(af))	
	6 000 m	15 000 m
$L_{A,max}$ [dB]	**-4.1**	**-3.0**
$EPNL$ [dB]	**-4.1**	**-2.8**
SEL [dB]	**-3.5**	**-2.3**

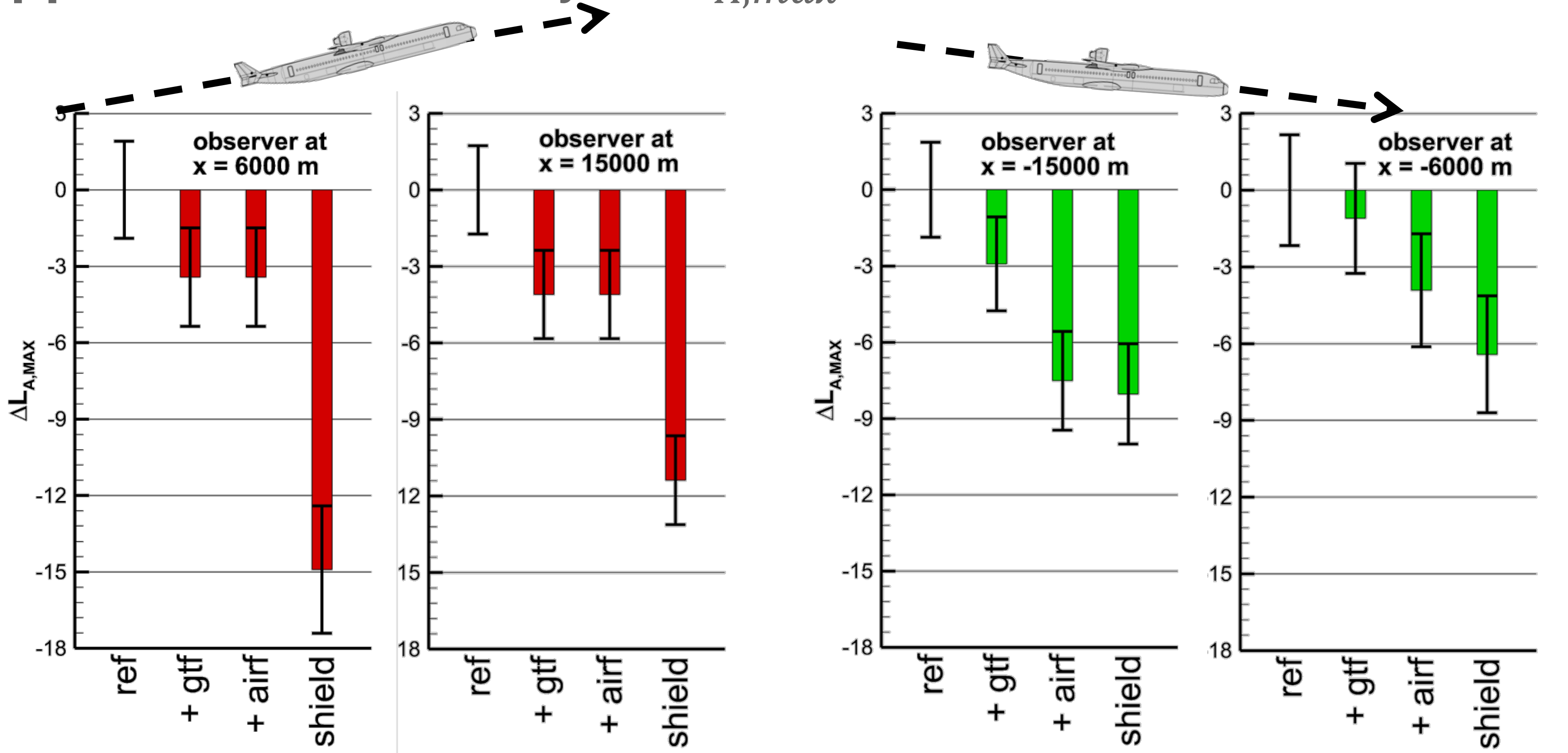
DOC [€/flight]	**-1482** (-7.34%)

- (less) fan noise reduction for fanex (already significant fan noise shielding)
- combination of shielding and gtf is most promising (all metrics: 2-4 dB reduction)
- low-noise airframe measures become very efficient (approach not shown here)
- significant DOC reduction

DLR

Technische Universität Braunschweig

application: uncertainty* of $L_{A,max}$ for low-noise measures



assumed modeling uncert.:
airfr.: gear & high-lift($\pm 1.4dB$), other($\pm 1dB$) eng.: fan**(ref $\pm 3.6dB$; gtf $\pm 4.2dB$), jet($\pm 1.5dB$)

- level differences & uncert. vary along simulated flight and per observer
- different conclusions for app. and depart.

*) uncertainties include covariances to account for correlated terms
**) shielding algorithm applied to all fan predictions ($\pm 3dB$)

presentation outline

- introduction
- motivation
- development
- application
- summary & outlook

summary: what did we achieve?

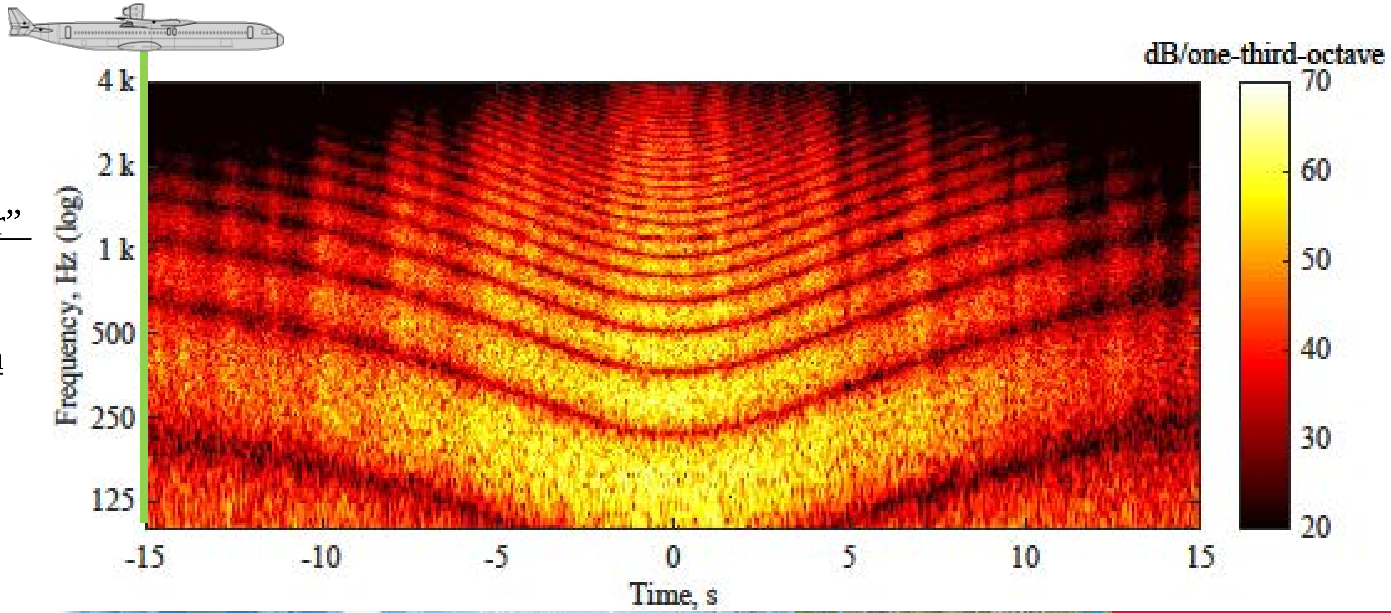
low-noise aircraft design (*tube-and-wing*)
- comprehensive noise assessment
    - design impact on flight performance / noise generation
    - multiple metrics & arbitrary observer locations
- engine installation effects (*no embedded design or BLI for now*)
- interface to external input data *(a/c design & noise)*
- tailored and optimized flight procedures
- basic uncertainty assessment

lessons learned
- must-have: high-fidelity engine simulation
- comparison with fly-over measurements:
    - essential input: flight data (FDR)
    - achievable level of agreement
        - perfect: purely coincidence
          (scaling, modeling capabilities & simplifications)
        - best: max. levels, trends/comparative analysis

outlook

1. engine installation effects: distributed propulsion and BLI
2. new DLR fan noise model (*PropNoise*)
3. “more electric aircraft” noise → *flight procedure design!*
4. noise-to-design (inspired by S. Rizzi, NASA)
   - cooperation with Empa (auralization & listening tests)
     - focus on novel vehicles and flight procedures
     - multiple observer locations
     - feedback loop: auralization → noise modeling

“gamechanger” along tailored approach: observer 4 km prior touchdown



acknowledgements:

DLR:
W. Dobrzynski, T. Otten, F. Wolters, M. Pott-Pollenske, and K.S. Rossignol
PhD students: **J. Blinstrub** and M. Koch
students: R. Ramdjanbeg, P. Krammer, C. Kott, and J. Ammermann

Empa (uncertainties and auralization):
B. Schäffer and R. Pieren

Thank you for your attention. Questions?

publications in context of joint research

1. L. Bertsch, W. Dobrzynski, S. Guérin: *Tool development for Low-Noise Aircraft Design*, AIAA-2008-2995, 14th AIAA/CEAS Aeroacoustics Conference, Mai 2008, Vancouver, British Columbia, Canada
2. L. Bertsch, W. Dobrzynski, S. Guérin: *Tool Development for Low-Noise Aircraft Design*, Journal of Aircraft, 47 (2), Seiten 694-699, DOI: 10.2514/1.43188, March - April 2010
3. P. Krammer, L. Bertsch, C. Werner-Spatz: *Multidisciplinary Preliminary Aircraft Design with Integrated Noise Analysis Capabilities*, DLRK 2009 121177, Deutscher Luft- und Raumfahrtkongress 2009, September 2009, Hamburg, Germany
4. L. Bertsch, O. Schneider, H. Hemmer, M. Hepperle, O. Macke: *Process Implementation for the System Evaluation of new Low-Noise STOL Transportation Concepts*, Paper No. 2, CEAS/KATnet II Conference on Key Aerodynamic Technologies, May 2009, Bremen, Germany
5. O. Schneider, S. Kreth, L. Bertsch: *Towards a Quiet Short Take-Off and Landing Transportation System: Concept Evaluation and ATM Integration*, IPLC-2010-0037, International Powered Lift Conference, October 2010, Philadelphia, USA
6. A. Bachmann, M. Kunde, M. Litz, A. Schreiber, L. Bertsch: *Automation of Aircraft Pre-design Using a Versatile Data Transfer and Storage Format in a Distributed Computing Environment*, Third International Conference on Advanced Engineering Computing and Applications in Sciences (ADVCOMP 2009), DOI: 10.1109/ADVCOMP.2009.22
7. L. Bertsch, G. Looye, T. Otten, M. Lummer: *Integration and application of a tool chain for environmental analysis of aircraft flight trajectories*, AIAA-2009-6954, 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), September 2009, Hilton Head Island, South Carolina, USA
8. L. Bertsch, G. Looye, E. Anton, S. Schwanke: *Flyover Noise Measurements of a Spiraling Noise Abatement Approach Procedure*, Journal of Aircraft, 48 (2), Seiten 436-448, DOI: 10.2514/1.C001005, March - April 2011
9. L. Bertsch, S. Guérin, G. Looye, M. Pott-Pollenske: *The Parametric Aircraft Noise Analysis Module - status overview and recent applications*, AIAA-2011-2855, 17th AIAA/CEAS Aeroacoustics Conference, 5-8 June 2011, Portland, Oregon, USA
10. L. Bertsch: *Noise Prediction within Conceptual Aircraft Design*, DLR Forschungsbericht, 2013, ISRN DLR-FB-2013-20

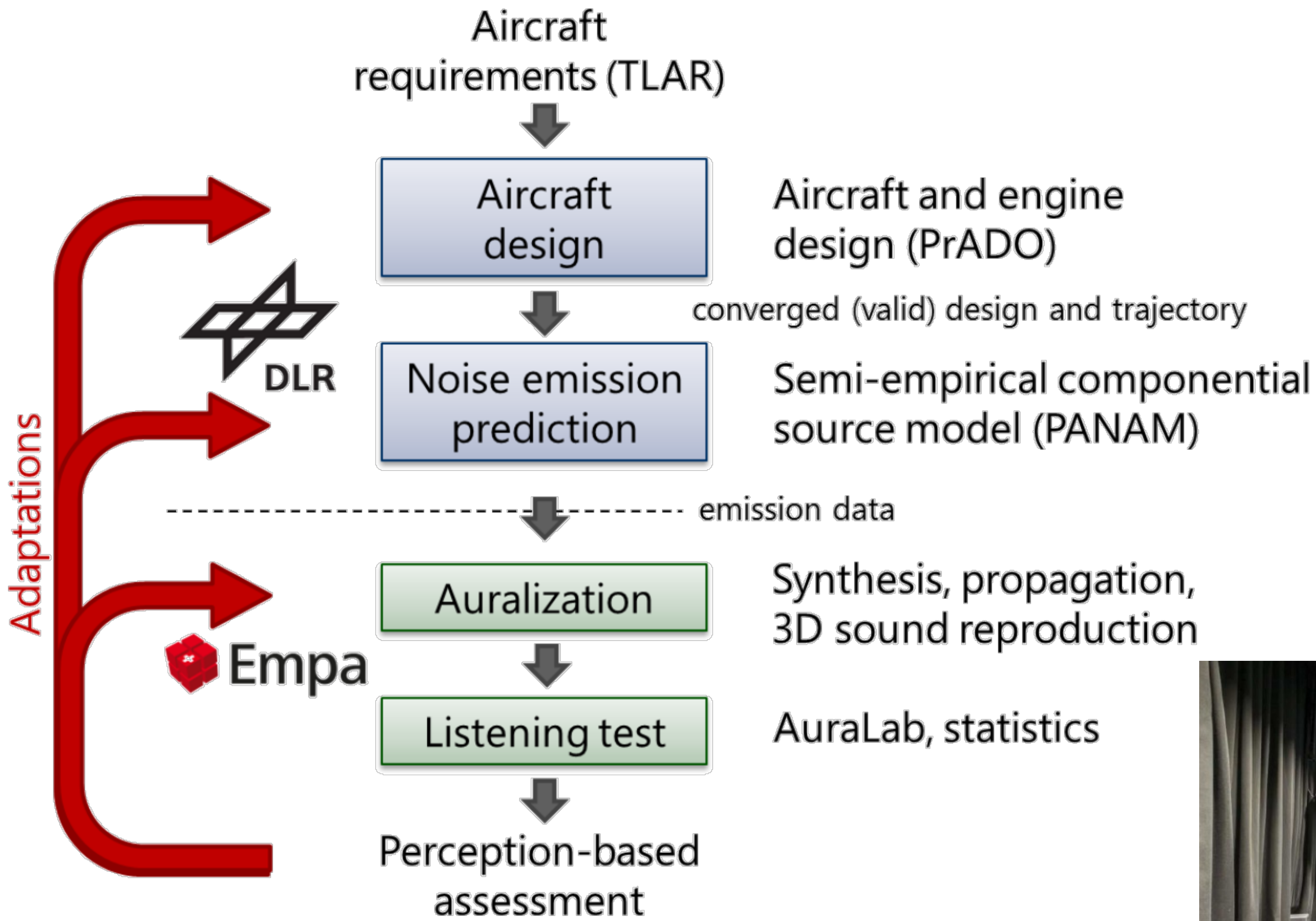
publications in context of joint research *(continued)*

11. H.H. Toebben, V. Mollwitz, L. Bertsch, B. Korn, D. Kuegler: *Flight Testing of Noise Abating RNP Procedures and Steep Approaches*, Journal of Aerospace Engineering, SAGE Publications Ltd. ISSN 0893-1321, 2013
12. L. Bertsch, W. Heinze, M. Lummer: *Application of an Aircraft Design-To-Noise Simulation Process*, 14th AIAA Aviation Technology, Integration, and Operations Conference, 10.2514/6.2014-2169, 16-20 June 2014, Atlanta, Georgia, USA
13. L. Bertsch, U. Isermann: *Noise prediction toolbox used by the DLR aircraft noise working group*, InterNoise Conference 2013, 15 - 18 September 2013, Innsbruck, Austria
14. K. Wicke, L. Bertsch: *SLED - Silent Leading Edge Devices, Abschlussbericht zum Flugzeugentwurf und der Systemanalyse*, Institut fuer Lufttransportsysteme, Hamburg, 2013, IB 328-2013/30
15. M. Pott-Pollenske, J. Wild, L. Bertsch: *Aerodynamic and Acoustic Design of Silent Leading Edge Devices*, 20th AIAA/CEAS Aeroacoustics Conference, 10.2514/6.2014-2076, 16-20 June 2014, Atlanta, Georgia, USA
16. T. Pfeiffer, E. Moerland, S. Freund, Y. J. Hasan, L. Bertsch, J. Flink: *ERGEBNISSE DES FLUGZEUGVORENTWURFSPROJEKTS FREACS (FUTURE ENHANCED AIRCRAFT CONFIGURATIONS)*, DLRK 2017, Muenchen, Germany
17. J. Blinstrub, L. Bertsch: *Towards an Immission-Based Noise Reduction Method for Conceptual Aircraft Design*, Notes on Numerical Fluid Mechanics and Multidisciplinary Design New Results in Numerical and Eperimental Fluid Mechanics X, Springer International Publisher, Switzerland, 2016, pages 687-697, ISBN 978-3-319-27278-5, ISSN 1612-2909
18. M. Arntzen, L. Bertsch, D. Simons: *Auralization of novel aircraft configurations*, 5th CEAS Air & Space Conference, 07. - 11. Sept. 2015, Delft, Netherlands
19. R. Ramdjanbeg, L. Bertsch, K.S. Rossignol, D. Simons: *Flap Side-Edge Noise Prediction within Conceptual Aircraft Design*, Notes on Numerical Fluid Mechanics and Multidisciplinary Design New Results in Numerical and Eperimental Fluid Mechanics X, Springer International Publisher, Switzerland, 2016, pages 731-742, ISBN 978-3-319-27279-5, ISSN 1612-2909
20. L. Bertsch, W. Heinze, M. Lummer: *Towards the System Noise Assessment of SFB 880 Vehicle Concepts*, SFB 880 - Fundamentals of high-lift for future commercial aircraft: Biennial Report, Braunschweig, 2015, ISBN 978-3-928628-67-9

publications in context of joint research *(continued)*

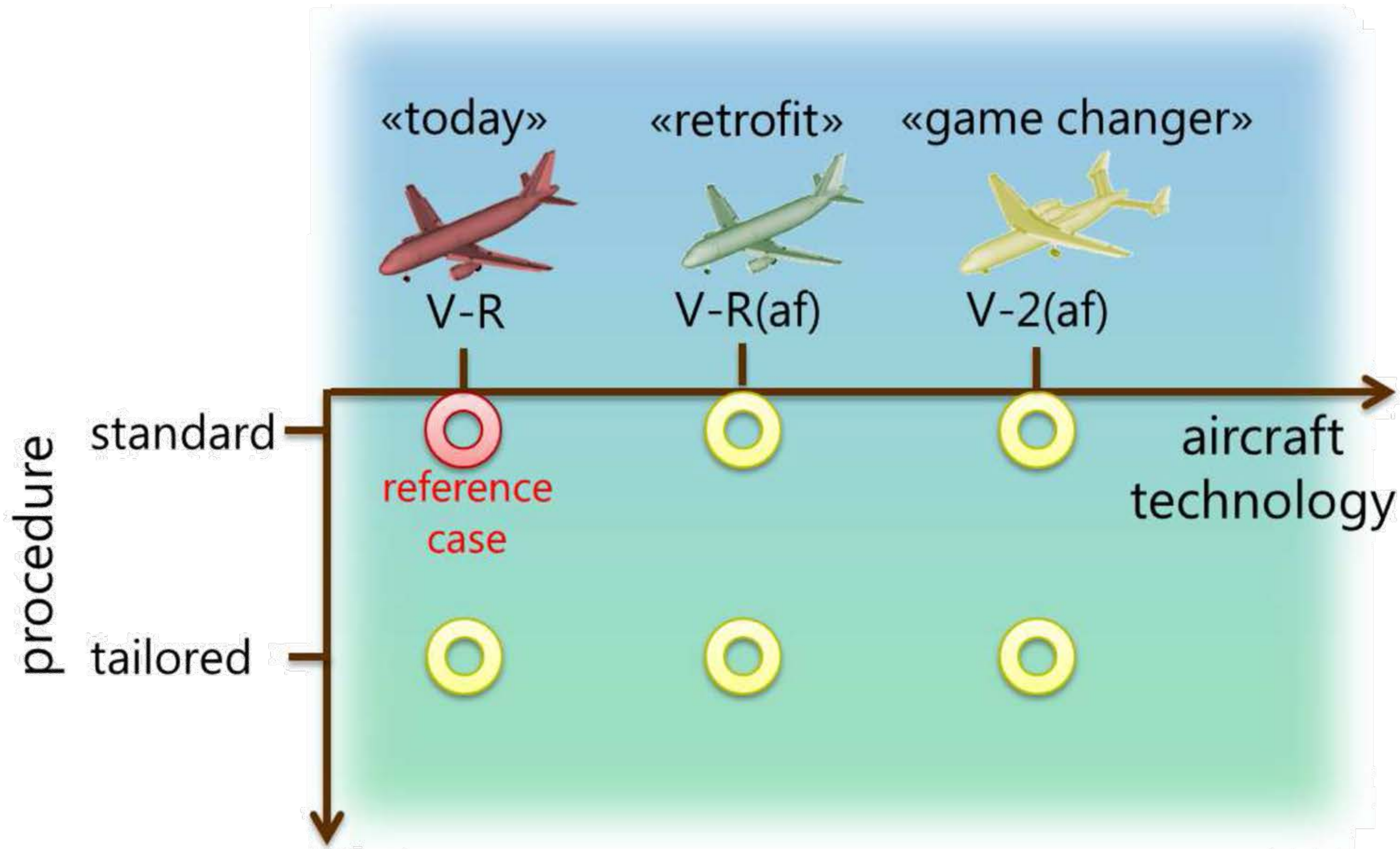
21. J. Blinstrub, W. Heinze, L. Bertsch, D.G. Simons, M. Snellen: *System noise assessment of an aircraft with Coanda flaps*, READ Conference 2016, 12.-14. Sep. 2016, Warschau, Polen
22. J. Blinstrub, L. Bertsch: *System noise assessment of SFB 880 concepts*, SFB 880 - Fundamentals of high-lift for future commercial aircraft: Biennial Report, Braunschweig, 2017, ISBN 978-3-928628-67-9
23. R. Radespiel, W. Heinze, L. Bertsch: *HIGH-LIFT RESEARCH FOR FUTURE TRANSPORT AIRCRAFT*, DLRK 2017, Muenchen, Germany
24. J. Blinstrub, L. Bertsch, W. Heinze: *Assessment of the Noise Immission along Approach and Departure Flightpaths for Different SFB880 Vehicle Concepts*, AIAA Aviation Forum, American Institute of Aeronautics and Astronautics, June 2018, Atlanta, Georgia, USA
25. D. Giesecke, M. Lehmler, J. Friedrichs, J. Blinstrub, L. Bertsch, W. Heinze: *Evaluation of Ultra-High Bypass Ratio Engines for an Over-Wing Aircraft Configuration Design studies*, submitted to Journal of the Global Power and Propulsion Society, 2017, - (-), pages - - -, DOI: -/-, ISSN - - -
26. L. Bertsch, Florian Wolters, Wolfgang Heinze, Michael Pott-Pollenske, Jason Blinstrub: *System noise assessment of a tube-and-wing aircraft with geared turbofan engines*, 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-0264, 08-12 February 2018, Kissimmee, Florida, USA
27. L. Bertsch, B. Schaeffer, S. Guérin: *Towards an uncertainty analysis for parametric aircraft system noise prediction*, 12th ICBEN Congress on Noise as a Public Health Problem, paper 3937, 2017, Zurich, Switzerland
28. L. Bertsch, B. Schaeffer, S. Guérin: *Uncertainty analysis for parametric aircraft system noise prediction*, submitted to the AIAA Journal of Aircraft, 2017, - (-), pages - - -, DOI: -/-, ISSN - - -
29. J. Delfs, L. Bertsch, C. Zellmann, L. Rossian, E. K. Far, T. Ring, S. C. Langer: *Aircraft noise assessment - From single components to large scenarios*, Energies Journal Special Issue: Towards a Transformation to Sustainable Aviation Systems, Energies 2018, 11, 429; doi:10.3390/en11020429
30. R. Pieren, L. Bertsch, J. Blinstrub, B. Schaeffer, J.M. Wunderli: *Simulation process for perception-based noise optimization of conventional and novel aircraft concepts*, 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-0266, 08-12 February 2018, Kissimmee, Florida, USA

backup slides: perception influence design



R. Pieren, L. Bertsch, J. Blinstrub, B. Schäffer, J.M. Wunderli: *Simulation process for perception-based noise optimization of conventional and novel aircraft concepts*, 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-0266, 08-12 February 2018, Kissimmee, Florida, USA

backup slides: perception influence design



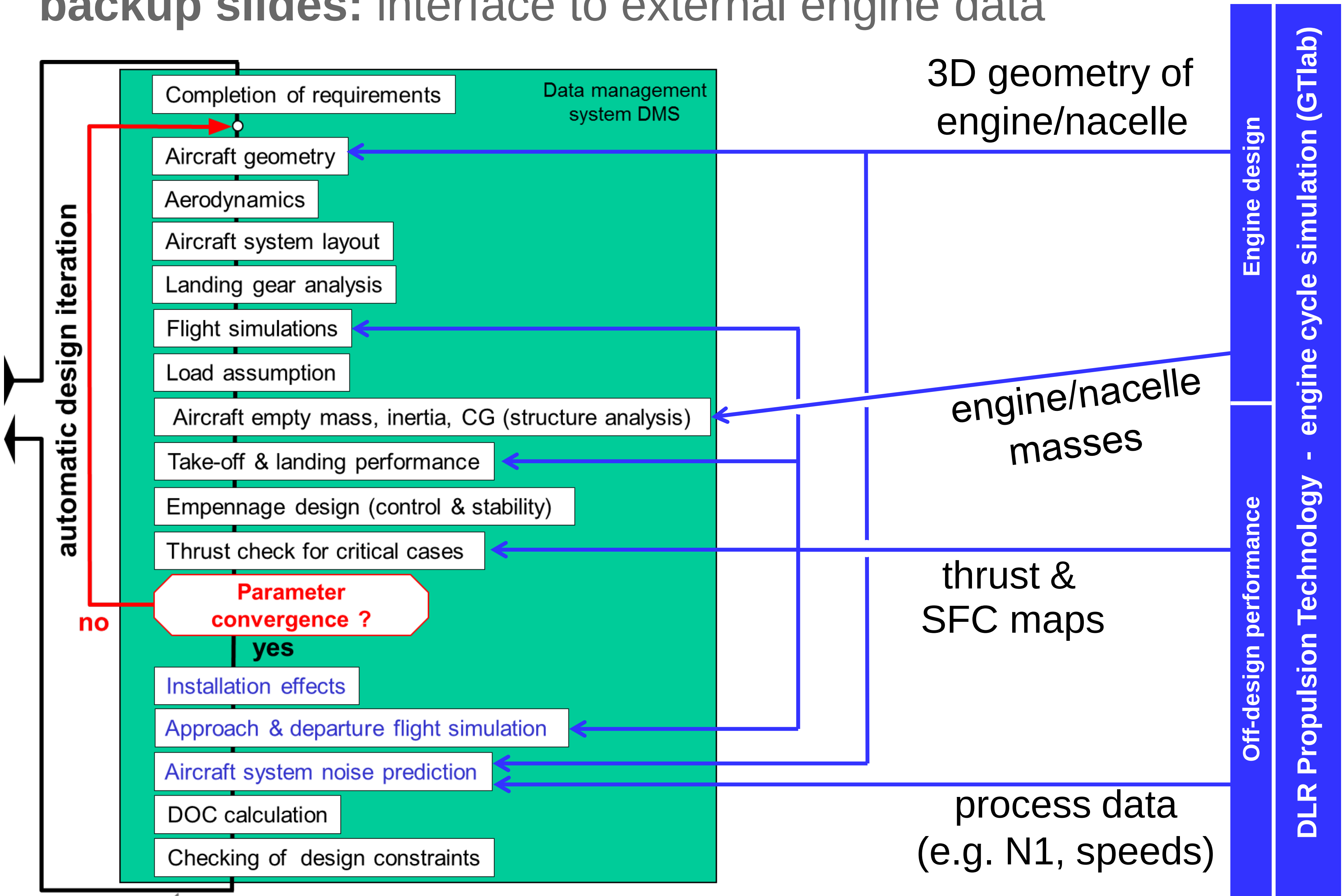
<u>furthermore</u>: 4 different observer locations

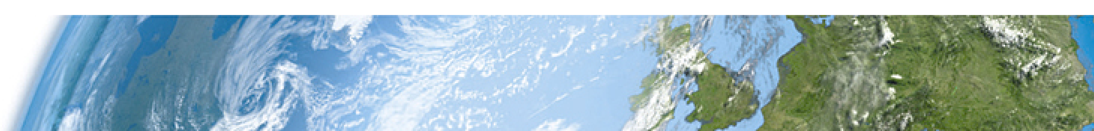
1. capture different flight phases
2. account for varying noise source ranking and distance / orientation

→ total of 24 stimuli for listening tests

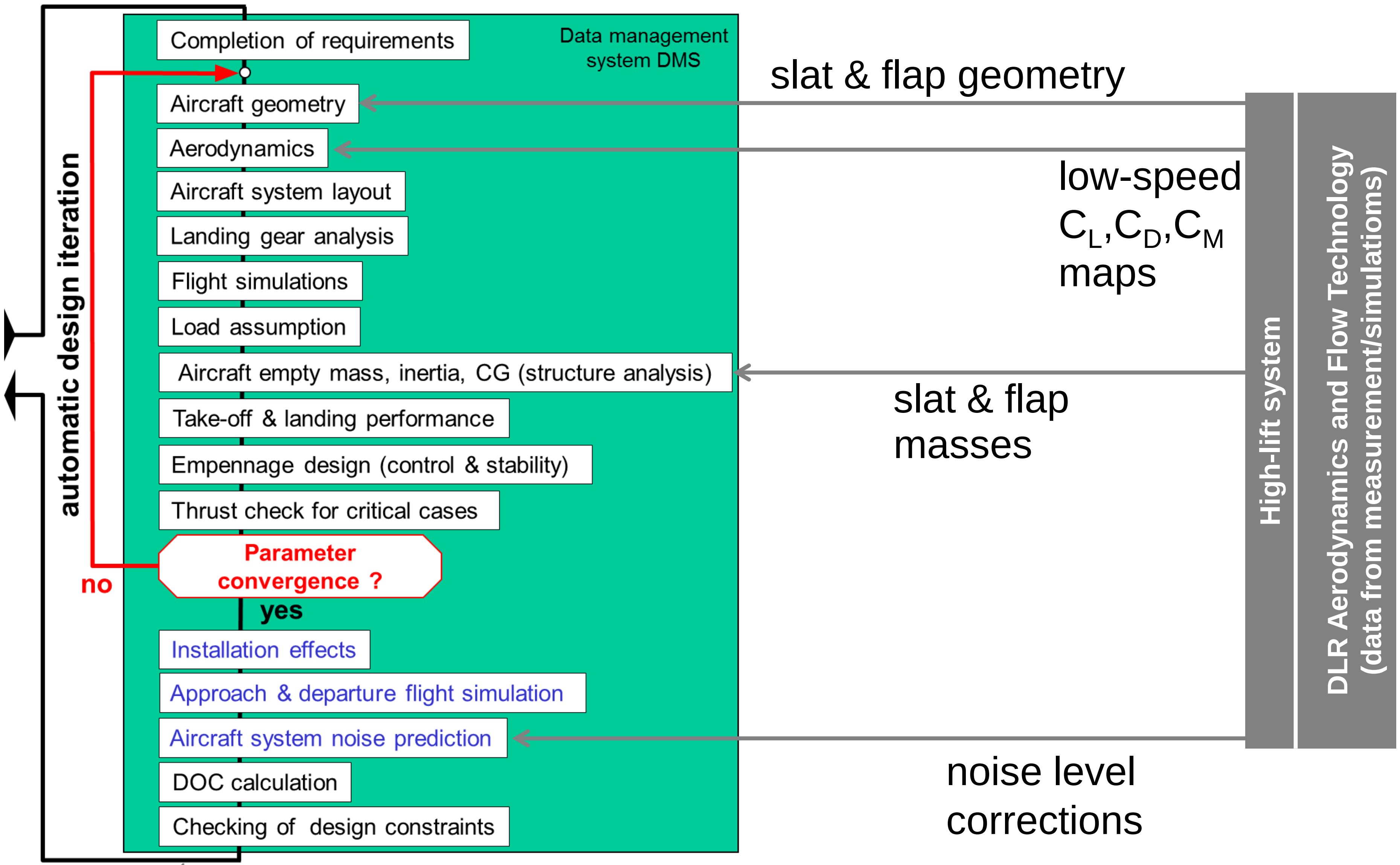
R. Pieren, L. Bertsch, J. Blinstrub, B. Schäffer, J.M. Wunderli: *Simulation process for perception-based noise optimization of conventional and novel aircraft concepts*, 2018 AIAA Aerospace Sciences Meeting, 2018, 10.2514/6.2018-0266, 08-12 February 2018, Kissimmee, Florida, USA

backup slides: interface to external engine data





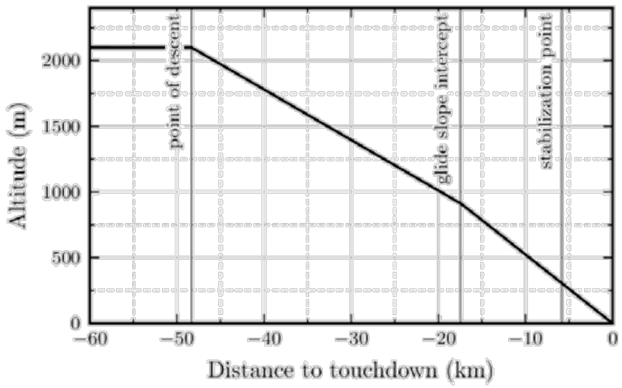
backup slides: interface to external high-lift data



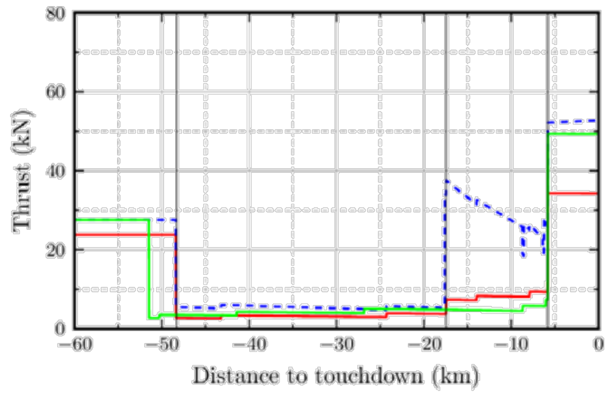
Figs. © Jason Blinstrub, DLR

backup slides: flight path adaption is essential

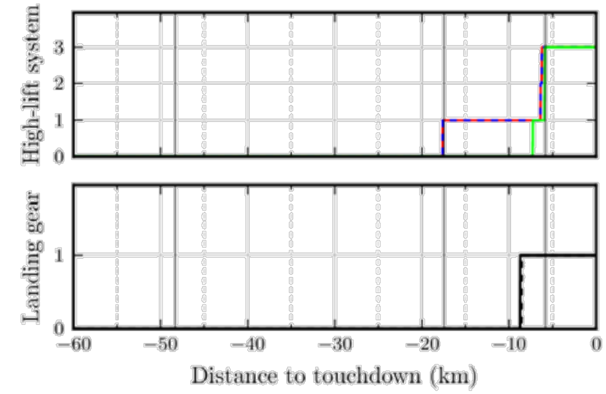
status quo: assessment of a/c design along fixed flight procedure



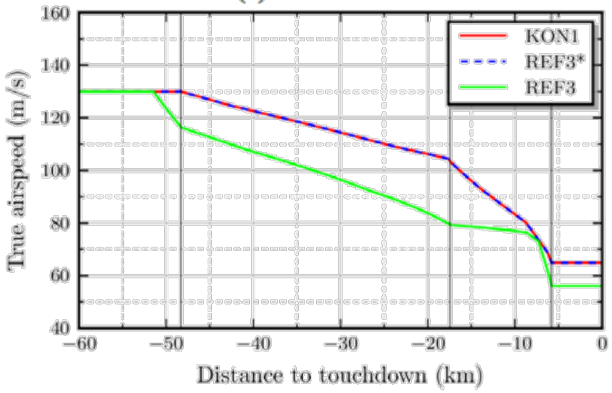
(a) Altitude



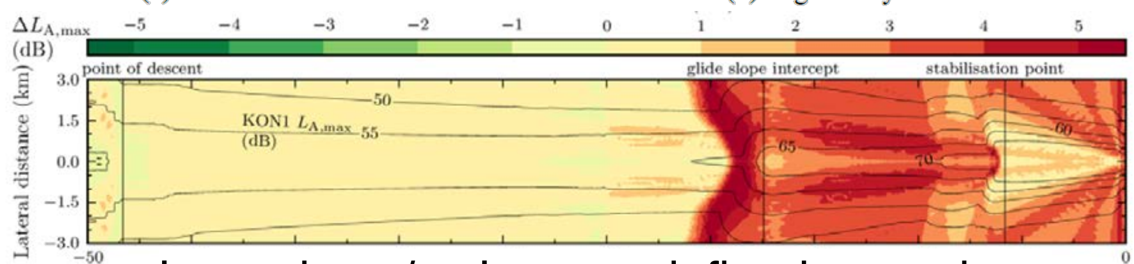
(c) Thrust



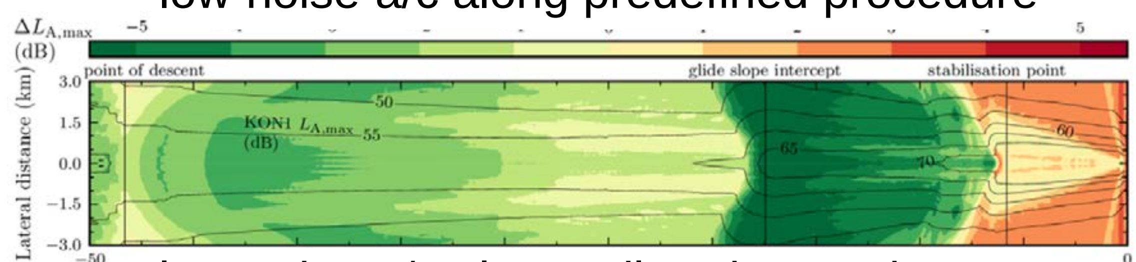
(d) High-lift system



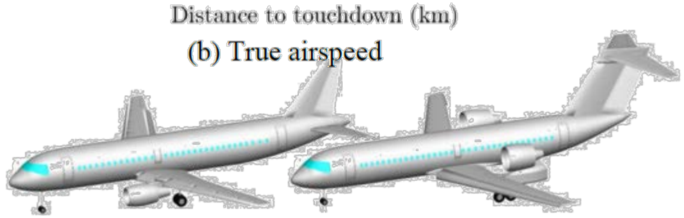
(b) True airspeed



low-noise a/c along predefined procedure



low-noise a/c along tailored procedure
(reduced speed, avoid thrust peaks, late flap/slat)



(a) KON1 (b) REF3

consequence: adapt flight procedure & focus on **IMMISSION**