Temperature offsets in AMDAR and other airborne measurements

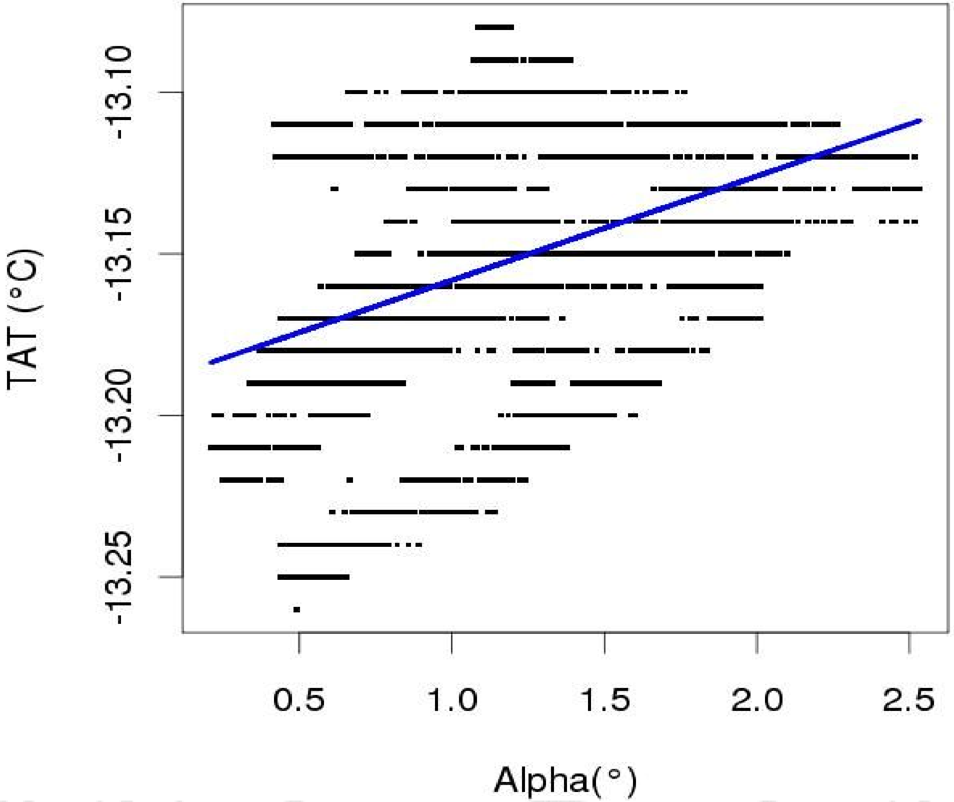
Clemens Drüe

Universität Trier
Umweltmeteorologie
Fachbereich VI
54286 Trier
druee@uni-trier.de

Motivation

- **Systematic errors**
  - measurements depend on flight dynamic state
- **Example:**
  - Dornier 228
  - TAT vs. angle of attack: 0.05 K/°
- **Most maneuvering during takeoff & approach**
  - here E-AMDAR takes profiles

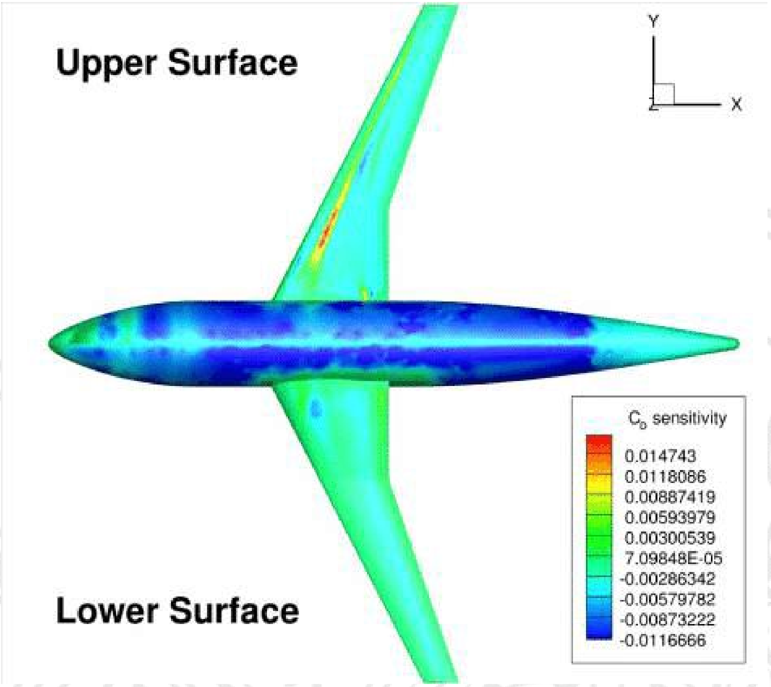
Clemens Drüe, IMUK Hannover

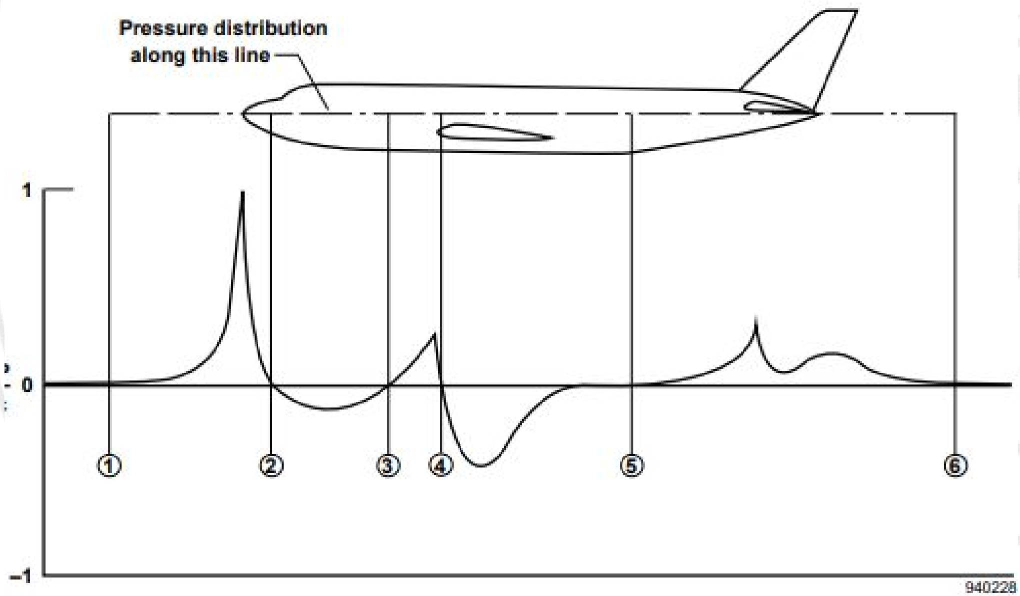


Highly structured flow

- **Flow field around aircraft**
- **Complex flow field**
  - flight speed below but same order as sound speed
  - Bernoulli effect, standing waves, harmonics.
- **Depending on**
  - airspeed
  - loading
  - (wing) configuration
- **p = f(x,y,z,v, …)**

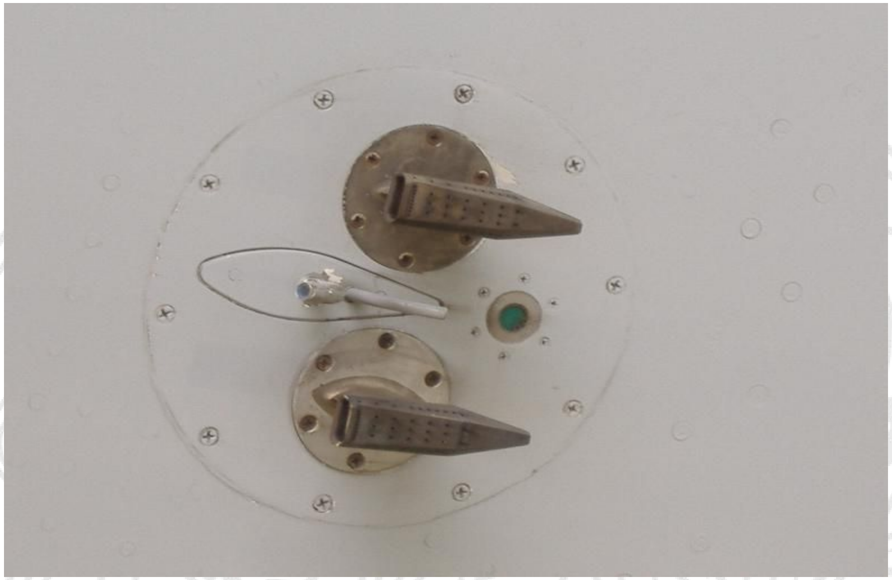
(Palacios, F et al. 2014)





(Palacios, F et al. 2014)

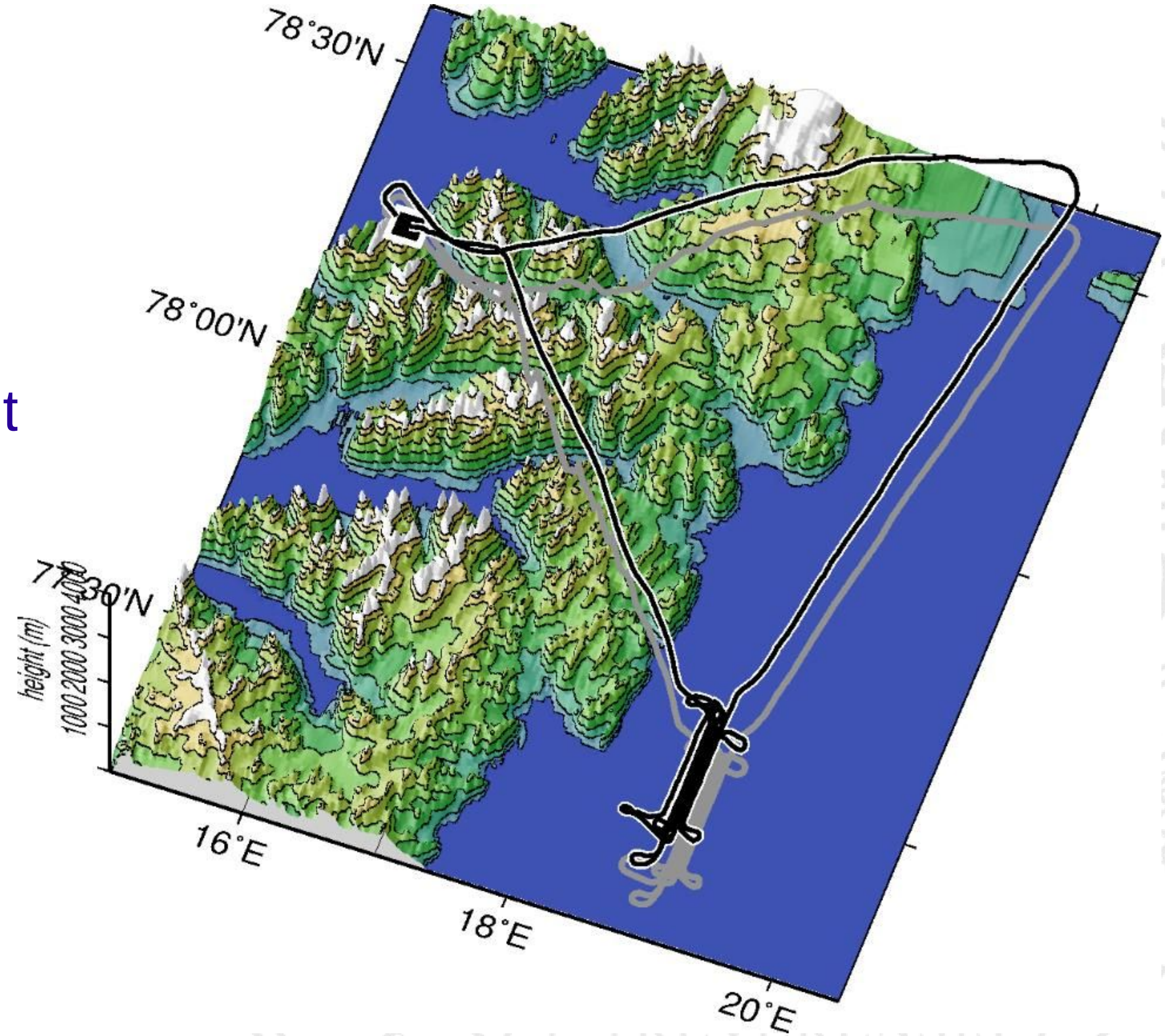
Thermometer housings (Rosemount)



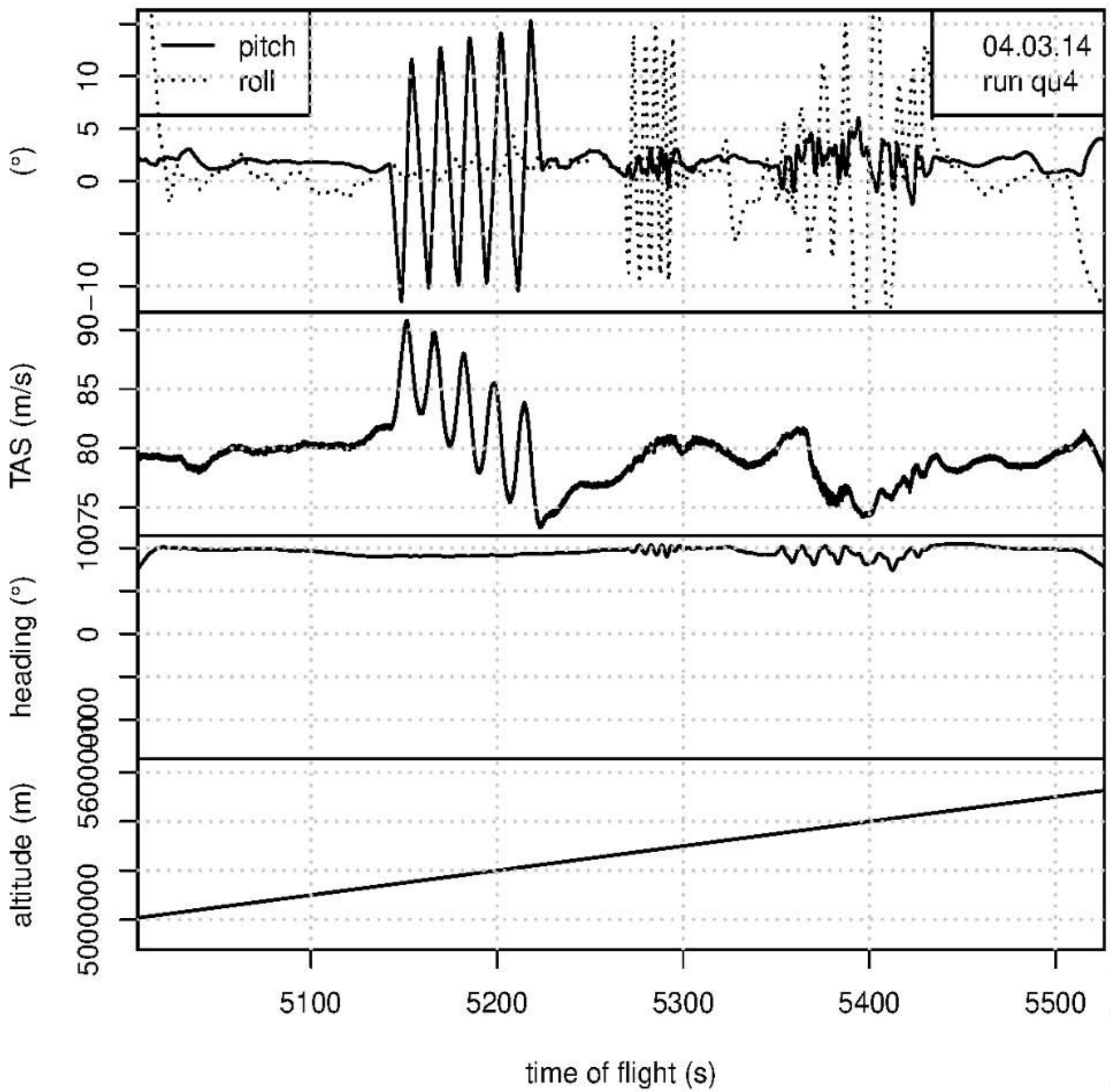
Solution in-flight calibration

- **Research aircraft:**
  - custom routine
  - lowest effort, maximum accuracy
  - only for measurement configuration

- **Commercial aircraft**
  - regulatory procedure
  - costly process, maximum reliability
  - for all nominal maneuvers



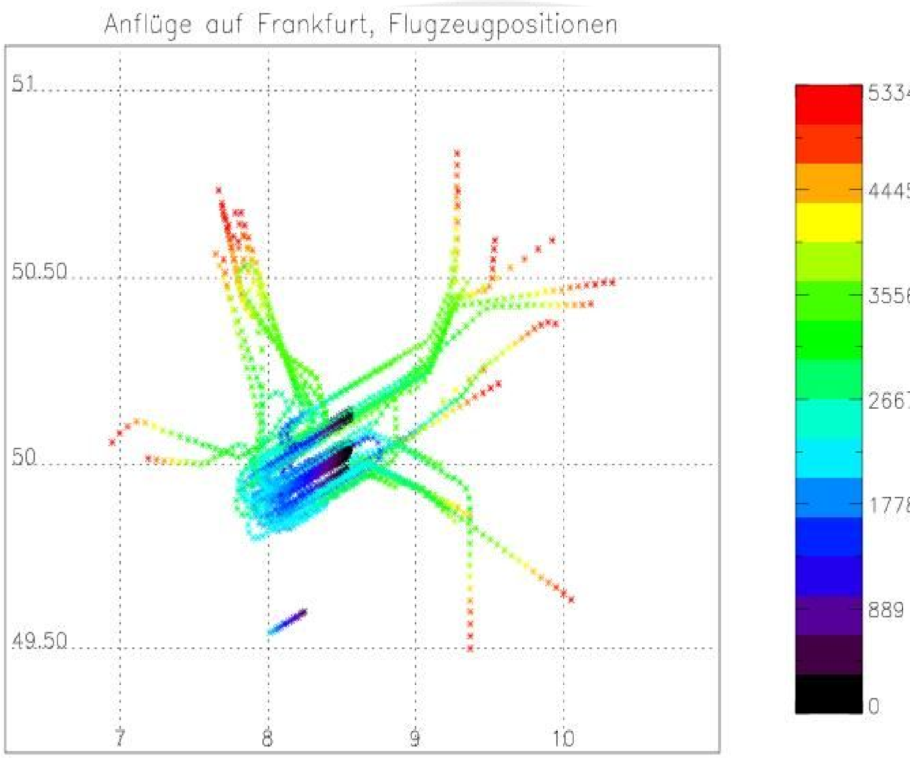
Data example (LEAST experiment 2014)



Initial Error study: Data Set EDDF

Dataset by DLR

- AMDAR data acquired by DLR from Lufthansa
- 22 days in 2004
- Descents to Frankfurt (FRA)
- High-resolution, high-frequency data
- Same airline / same software

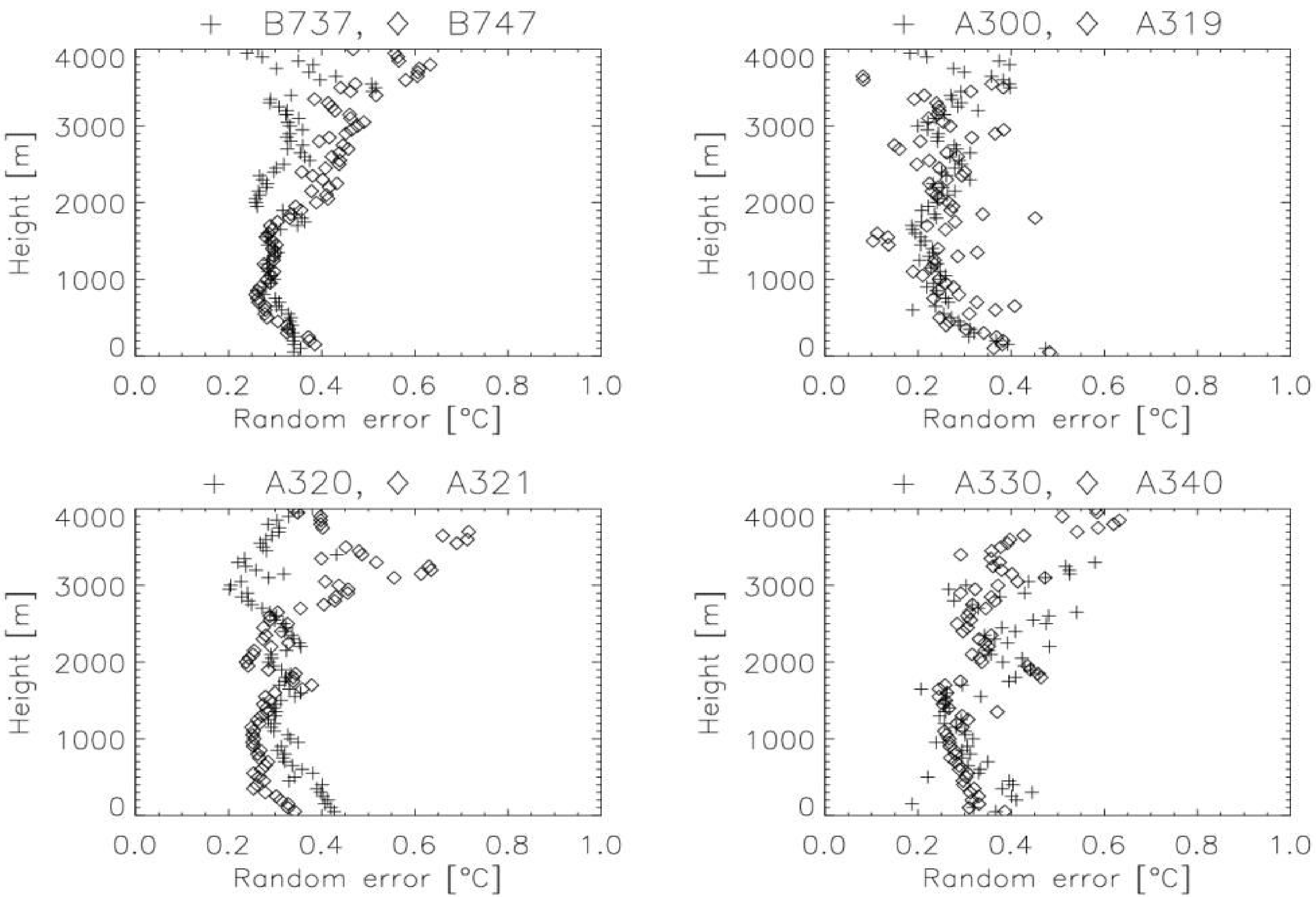


Aircraft-type dependent

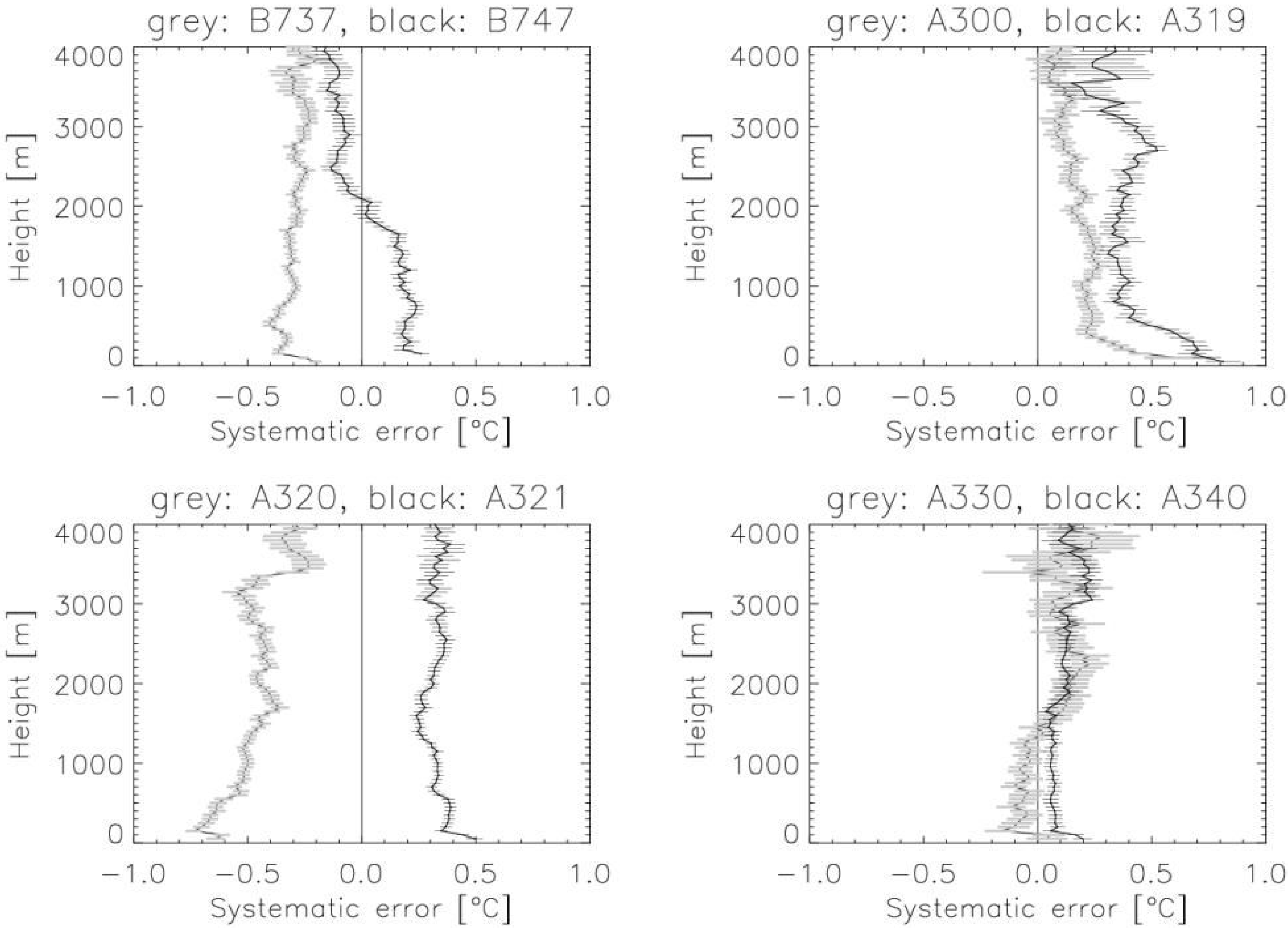
- bias
- root-mean-square (rms) error

Hourly mean profile (all types) used as reference

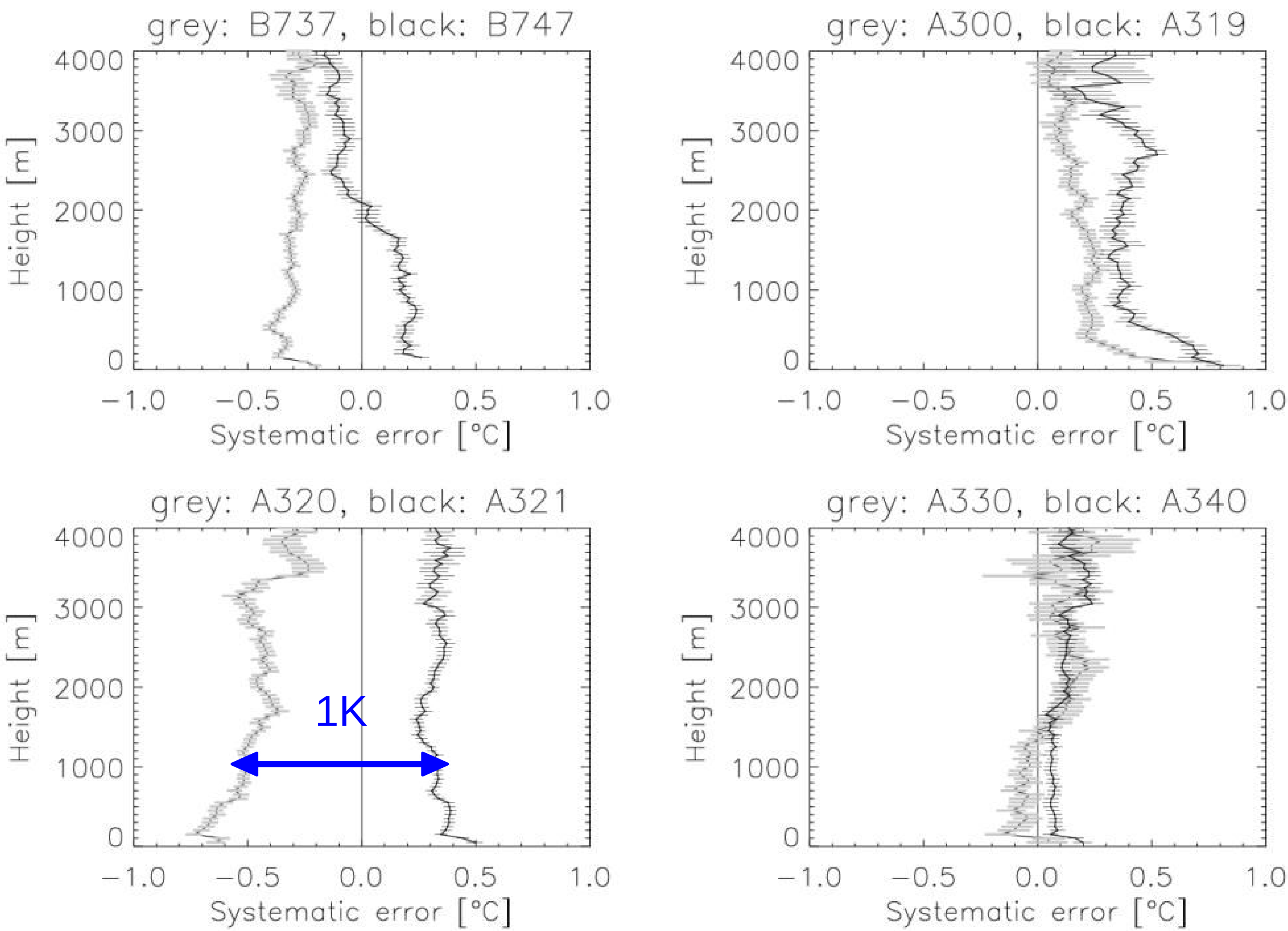
Random temperature errors



Systematic temperature errors



Error study: Systematic Temperature Errors



W. Frey, IMUK

Error study: Temperature Errors

All rms errors around 0.3 - 0.4 K

Differing systematic bias values:

a/c type	systematic error behavior
B737	0.35 K too cold
B747	no specific trend, slight decrease with altitude
A300	0.2 K too warm
A319	**0.3 - 0.4 K too warm**
A320	**0.5 K too cold**
A321	0.3 K too warm, comparable to A319
A330	no significant trend, slight increase with altitude
A340	0.1 K too warm

Error study: Wind error vector

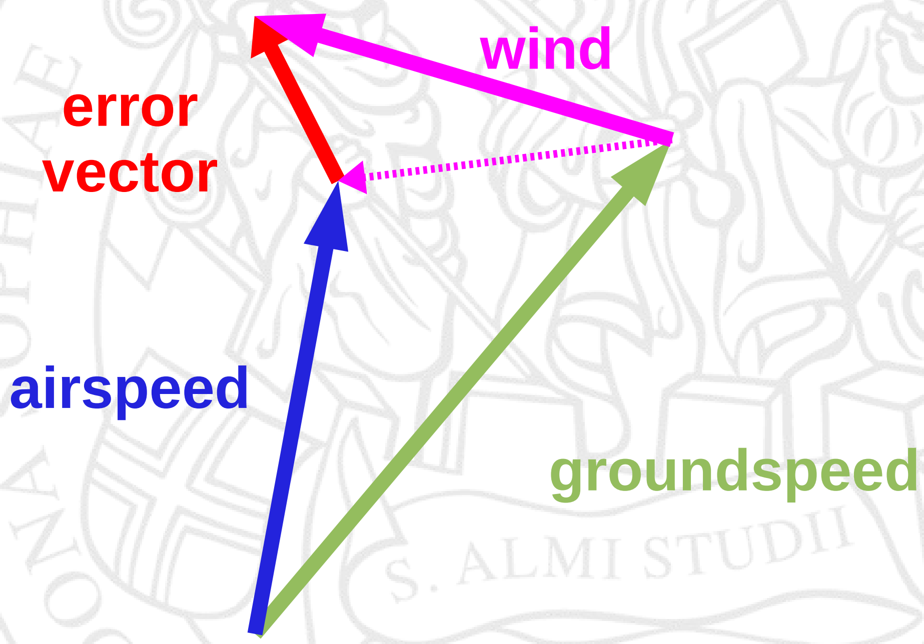
Wind speed (scalar) error seems completely random

Assumption: Aircraft-fixed error vector

Calculate errors in wind components

longitudinal and
lateral to flight path

Error vector presumably not only type dependent

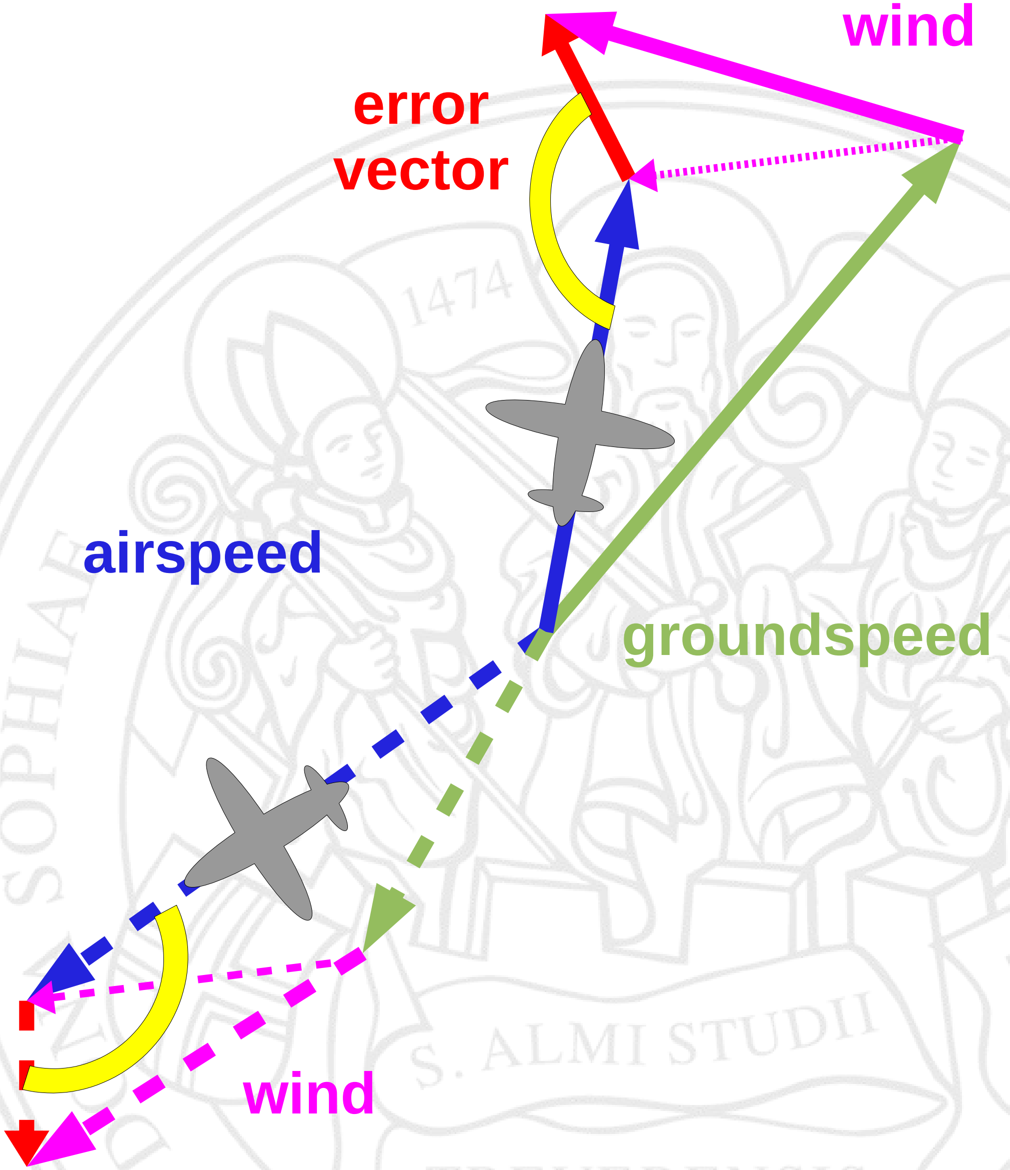


Error study: Wind error vector

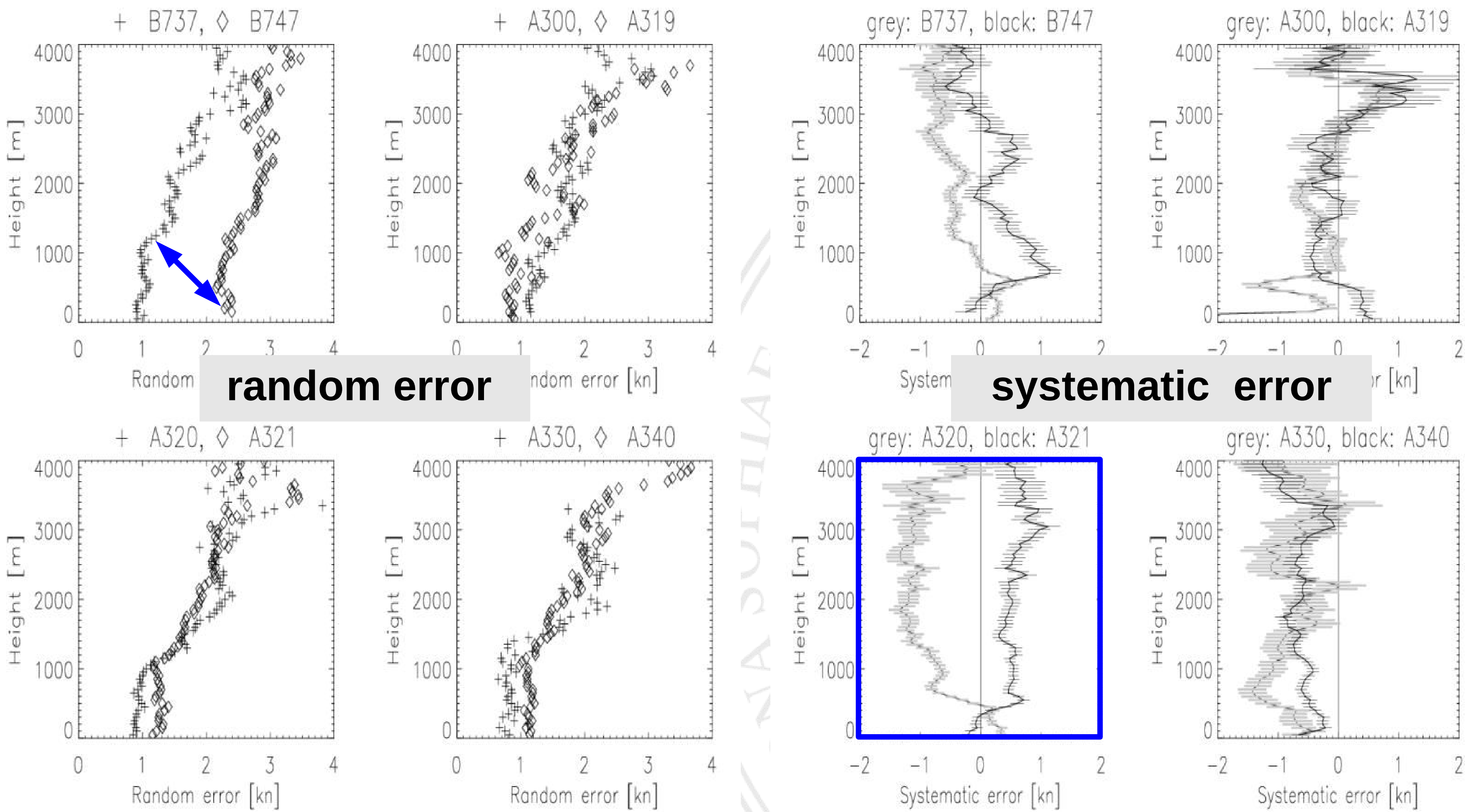
- **Wind speed error:**
  Aircraft-fixed error vector

- **Errors in**
  - wind speed and
  - wind direction
- **depend on flight direction**

- **Heading**
  - needed for correction
  - not (yet) in AMDAR data

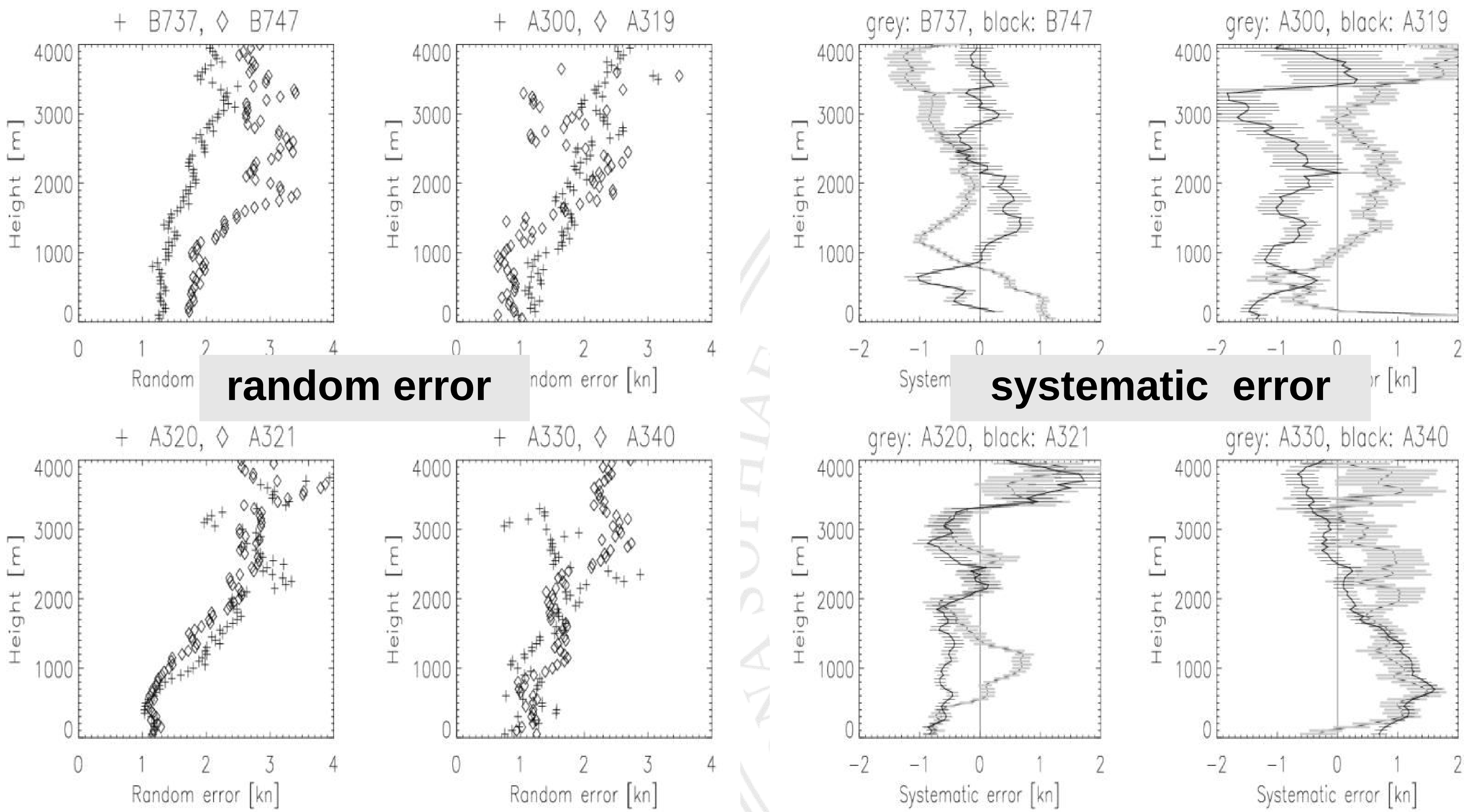


Longitudinal wind component



W. Frey, IMUK

Lateral wind component



Influencing parameters

Roll angle

raw estimate from AMDAR

Mach number

substitute: ground speed

Heading

substitute: ground track direction ("track")

Pitch

substitute: ascent/descent rate or pressure change

slip angle

substitude: lateral acceleration (not from AMDAR)

Weight-over-Delta

substitute: static pressure or flight duration

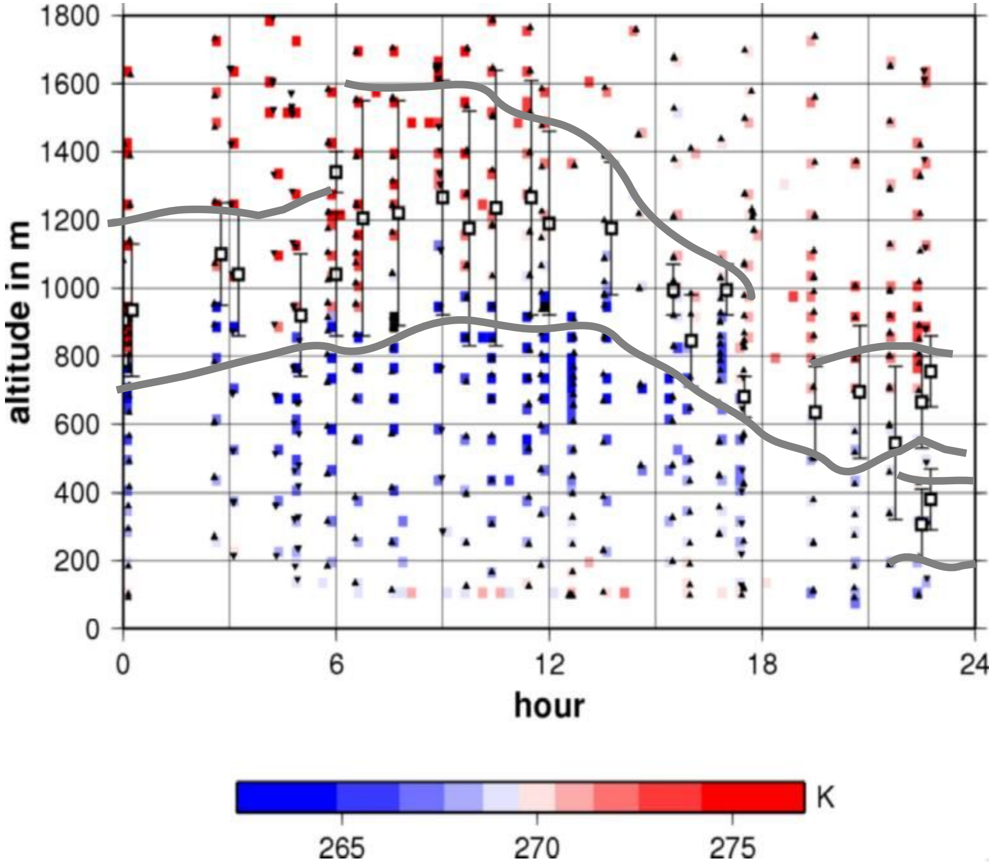
Comparison: AMDAR vs. ground-based profiler

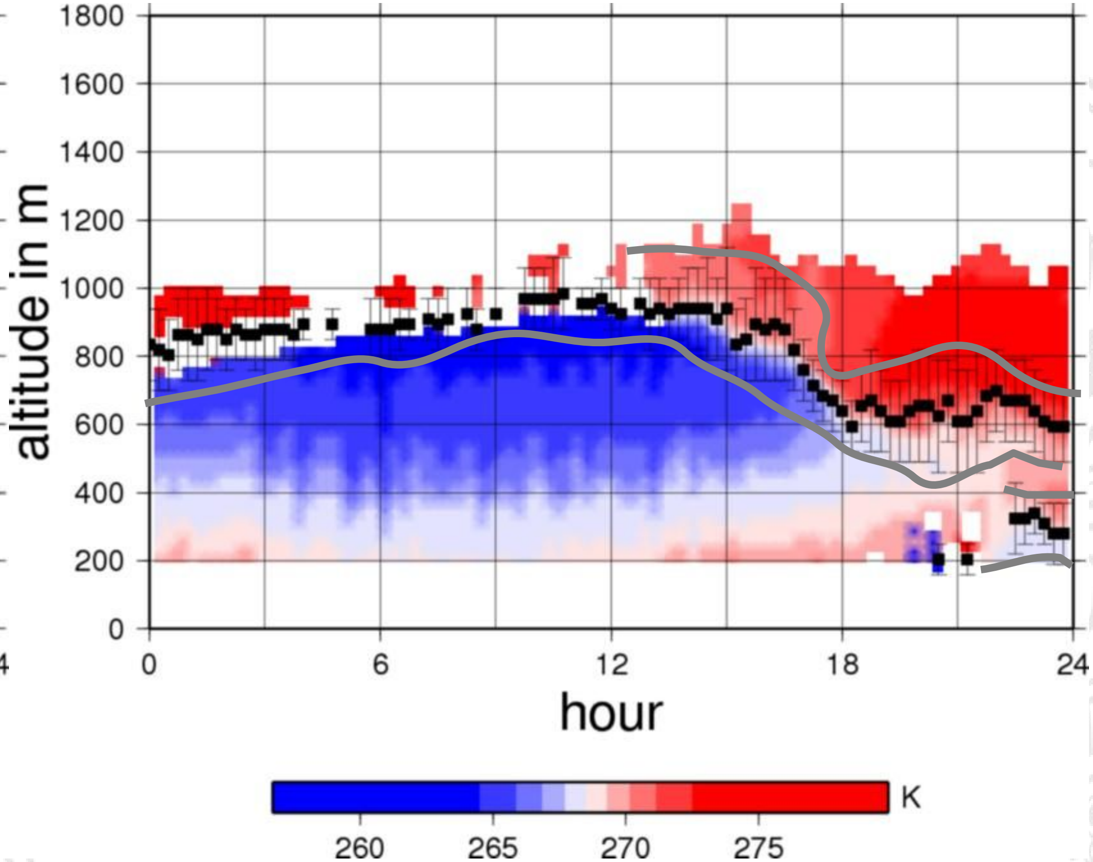
- **Scintec AP1000 / RASS**
  - max. range 3000 m
  - vertical profiles of
    - (virtual) temperature
    - wind speed / direction
- **data available**
  - since Dec. 2005
  - 100 m to 1750 m height every 30m
  - every 15 min

picture courtesy of Scintec AG

WT/RASS at Frankfurt

Data example: 15 Jan 2006





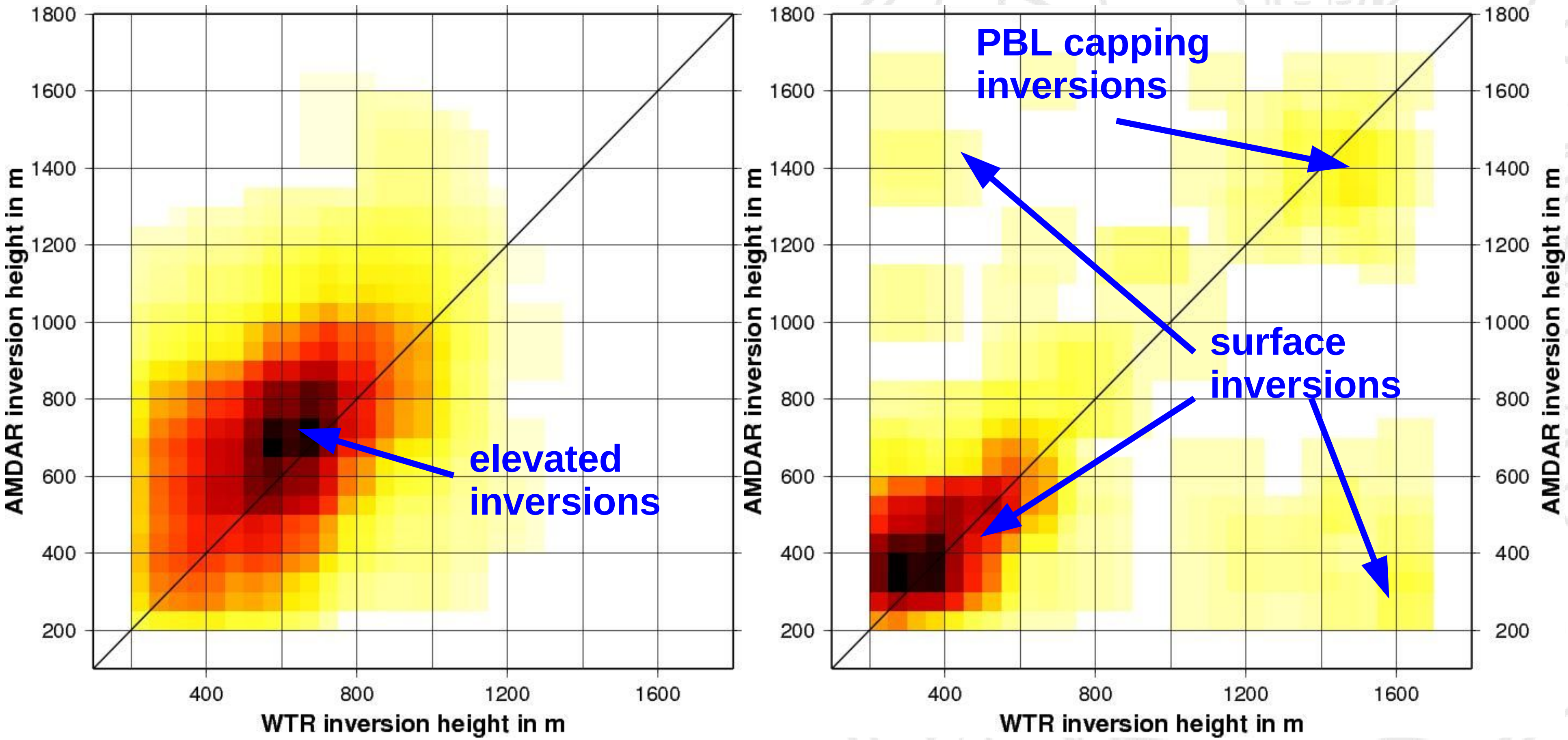
AMDAR

WTR/RASS

Inversion overlap

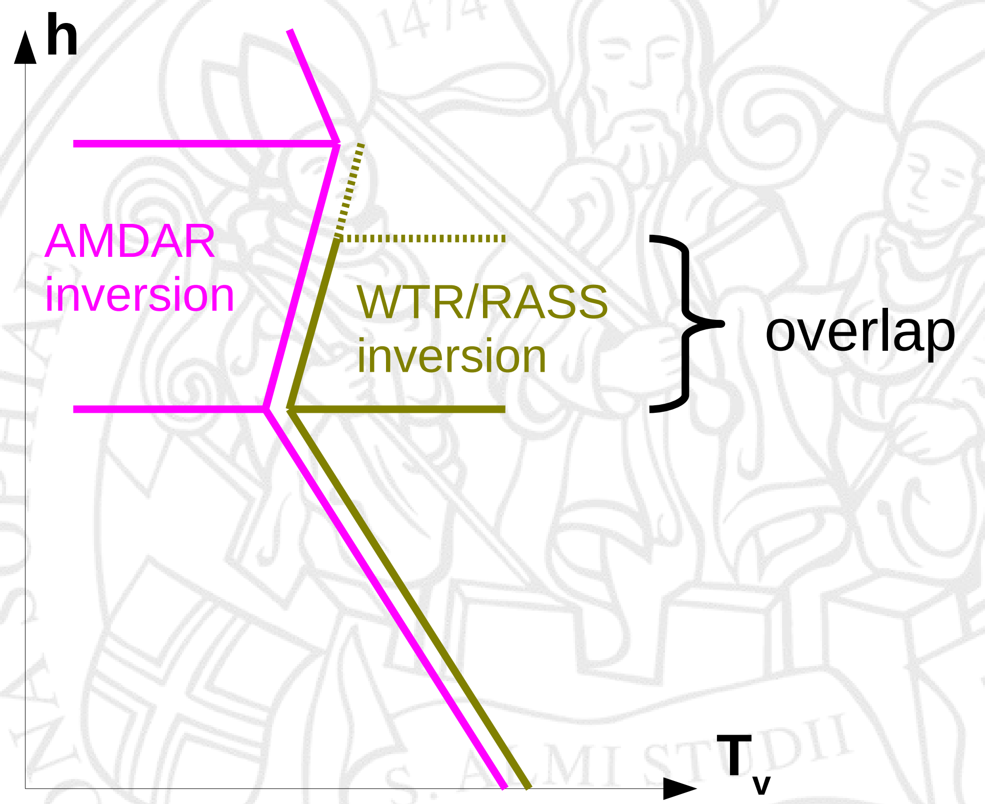
January: 1074 cases

July: 111 cases



WTR/RASS range issue

- **Inversion top above WTR/RASS range**
  - base detected by both
  - top detected in AMDAR
  - WTR/RASS sensed inversion ends at range
  - overlap only in lower part of inversion
- **shallower inversion**
- **downward shift of median height**

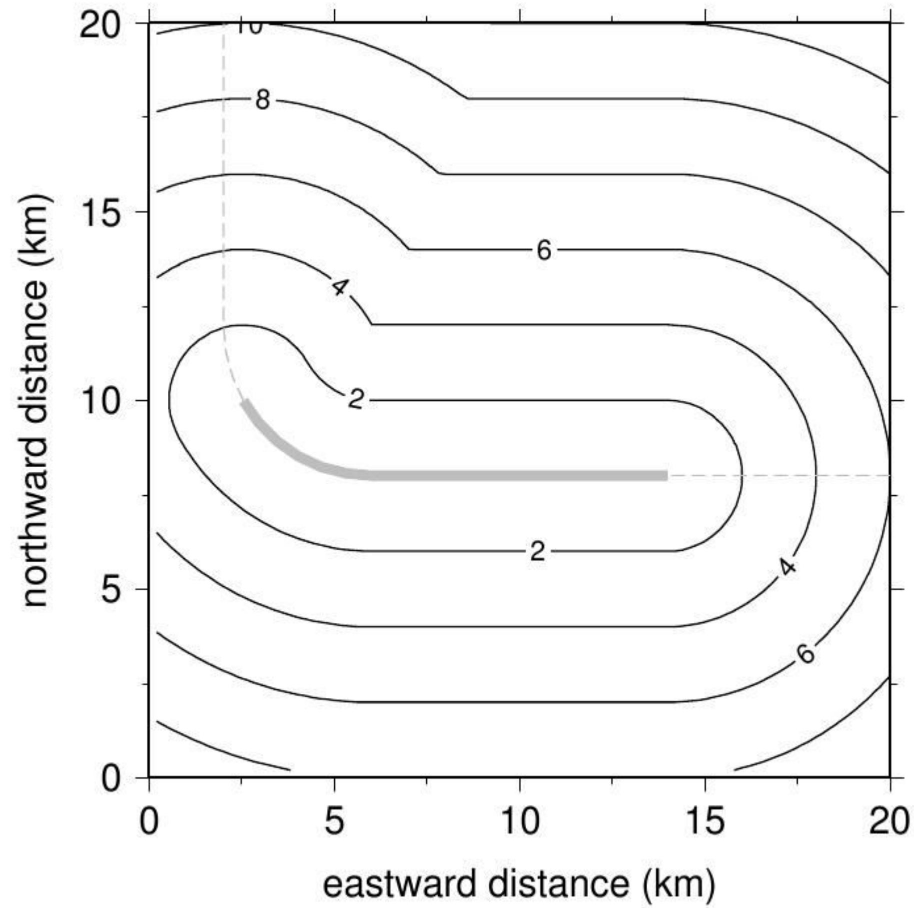


Objective / Method

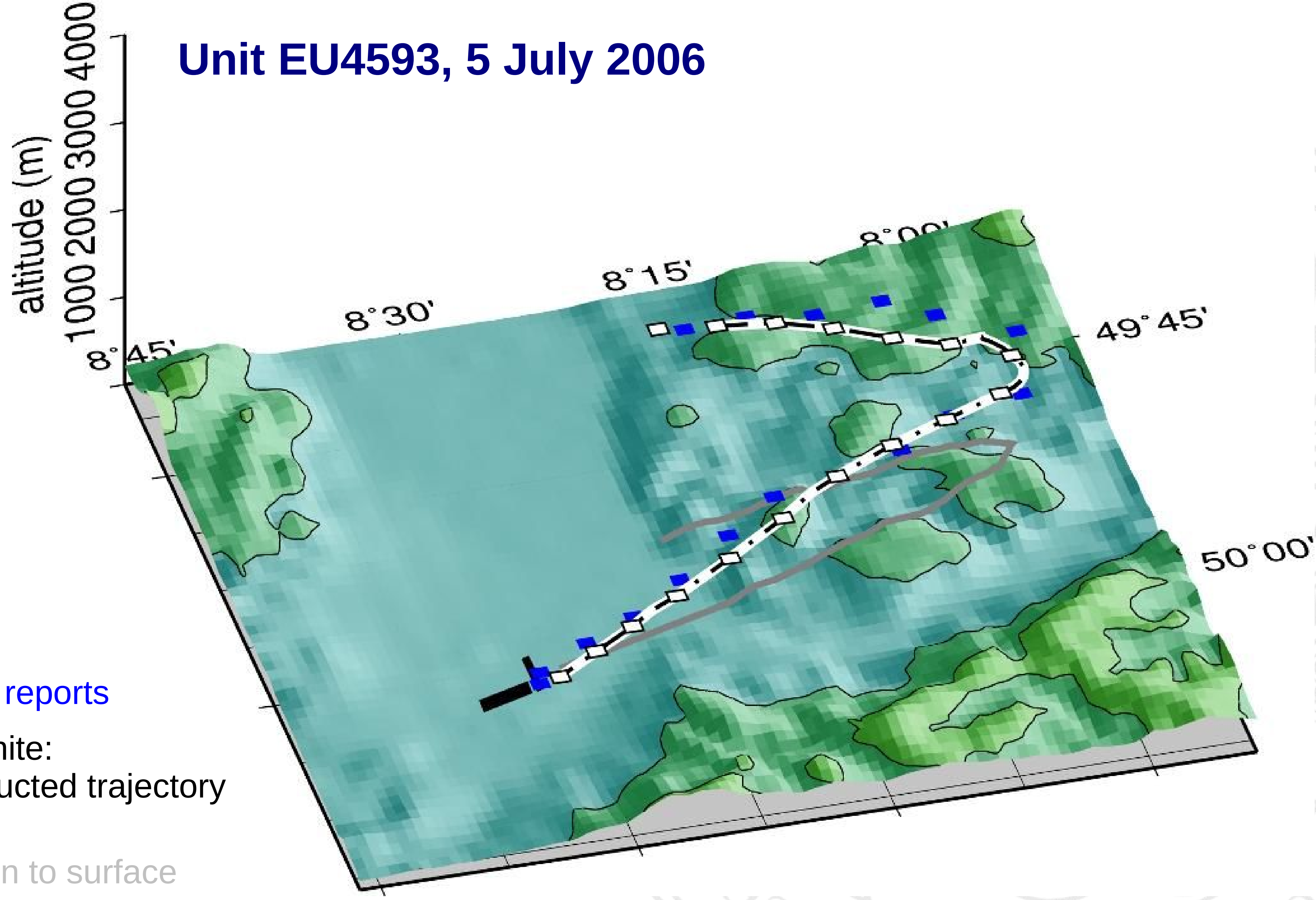
- **Flight dynamic data needed to model errors**
  - No flight-dynamic information transmitted
  - Radar data inaccessible
    Track identification impossible (anonymous identifiers)
- **Reconstruct flight dynamics**
  - Simplified flight simulator
    - BADA performance model for horizontal / vertical speed
    - Horizontal flight path templates
      (*N* straights, *N-1* constant-roll turns)
    - Variational solution using cost function
      - Minimal distance to AMDAR data positions
      - Minimal flight distance and turn angle
      - Mimimal difference between TAS and BADA speed schedule
      - ...

Flight simulator

- **Not straightforward**
  - Unsharp AMDAR reports
    - Time: seconds stripped
    - Position: seconds stripped
    - Height: small uncertainty
- **Ensure numerical stability**
  - Prevent Oscillations / Loops
  - Allow minor heading adjustments
  - Aircraft performance limits
- **Combination of**
  - Dimensional analyses
  - Manual tuning



Example: Approach to Frankfurt/Main

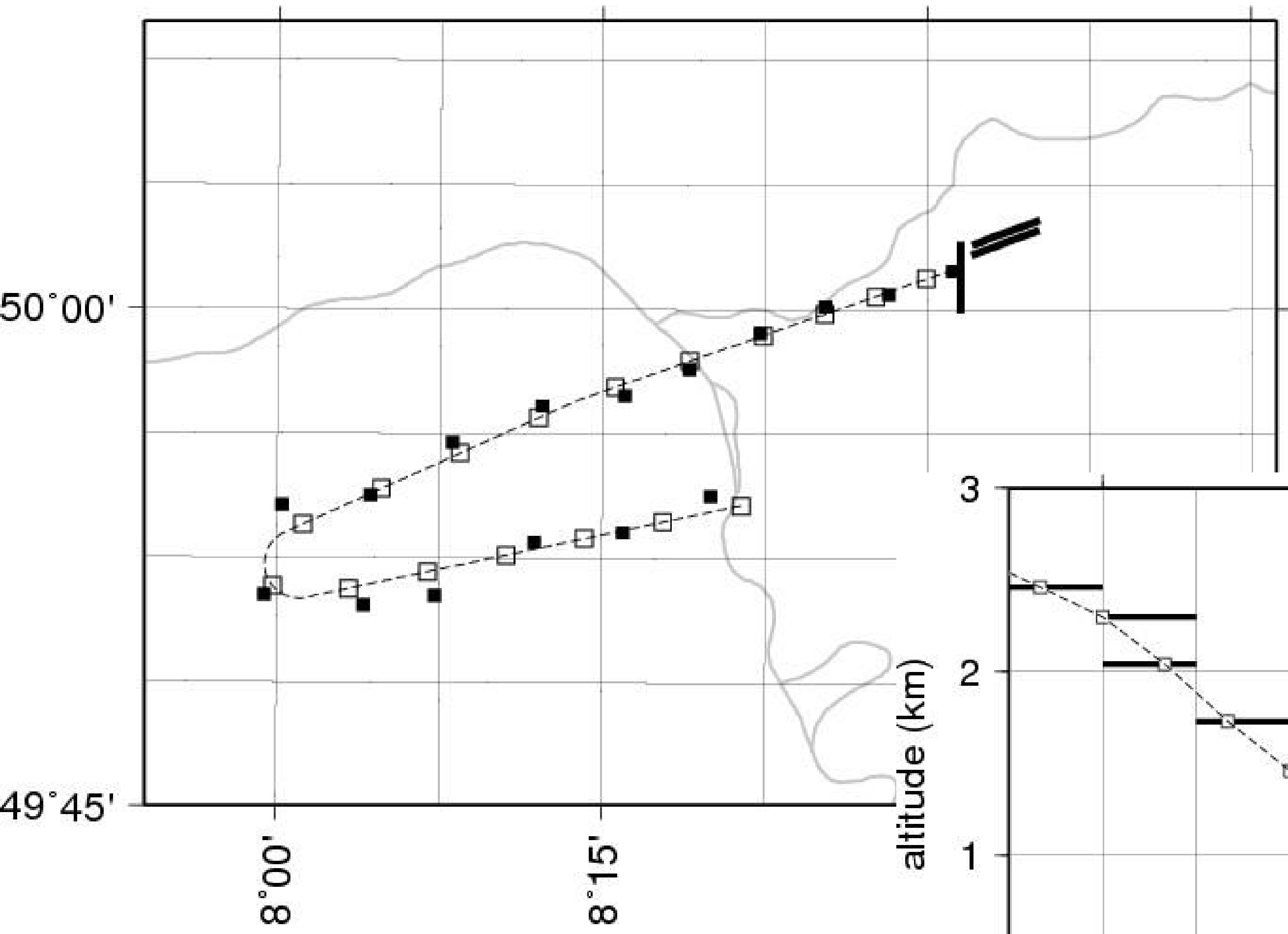


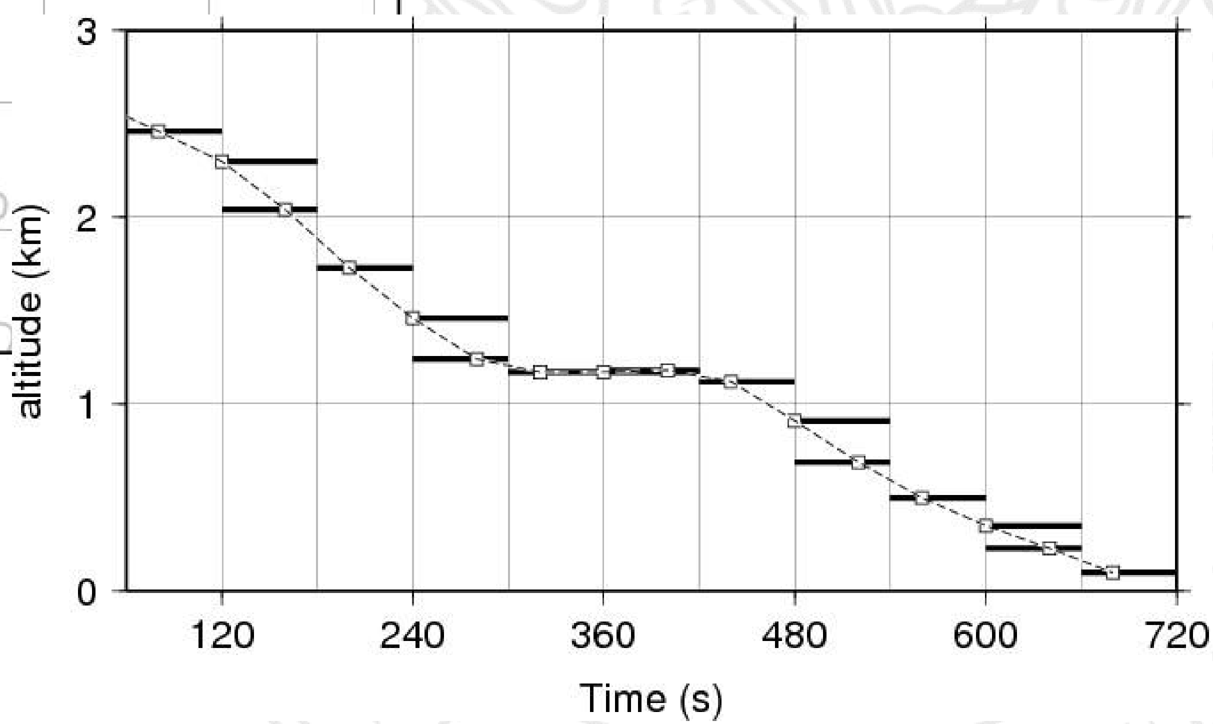
Blue:
AMDAR reports

Black/white:
reconstructed trajectory

Grey:
projection to surface

Horizontal / vertical





- ➔ **Approach of EU4593 to Frankfurt, 5 July 2006**

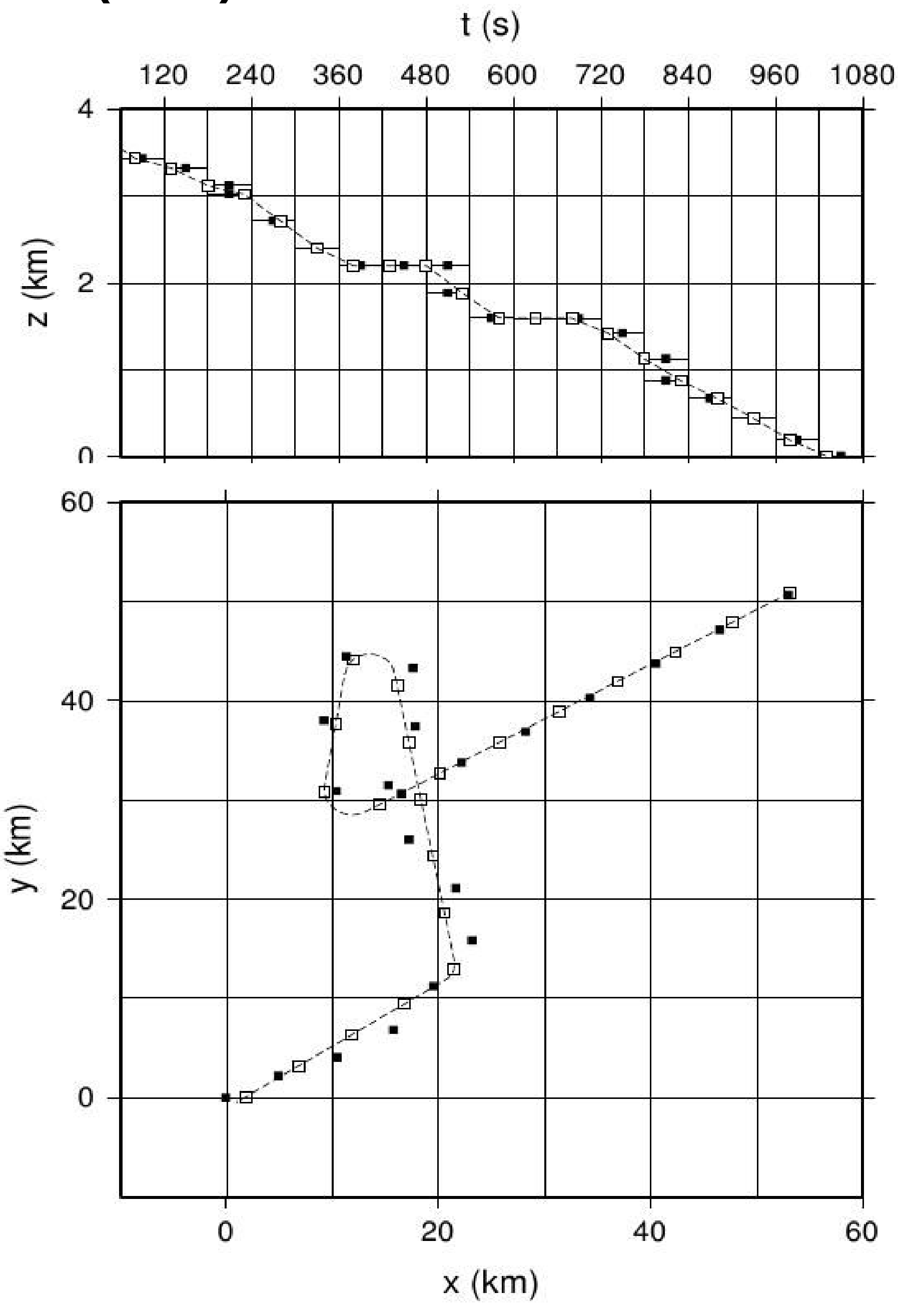
Validation

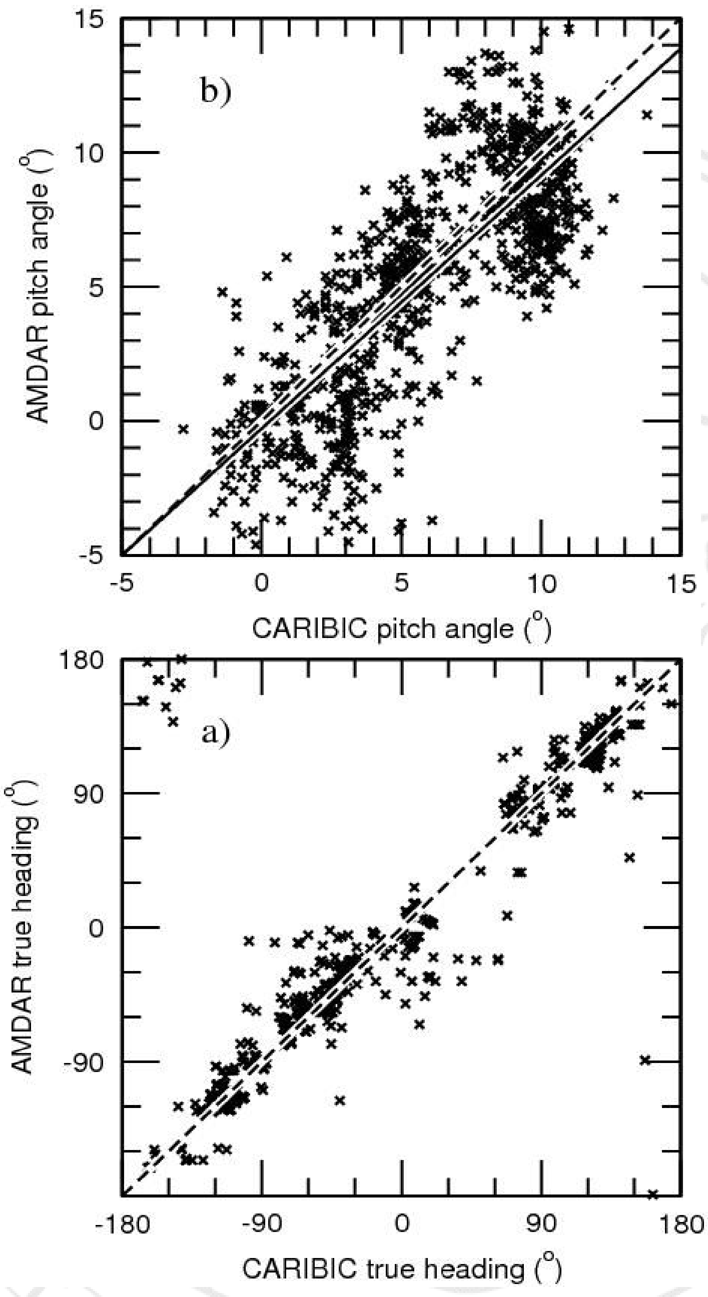
- **CARIBIC (civil aircraft for the regular investigation of the atmosphere based on an instrument container)**
- **Lufthansa A340-600 D-AIHE**
- **Records data at 1 Hz**
  - Scientific data (gas composition)
  - Meteorological data
  - Flight dynamic data
- **Pseudo-AMDAR reports generated**
  - Using DLH reporting scheme
- **Trajectory reconstructed from AMDAR**
  - Compared to actual recording

Pictures: MPI Mainz, www.caribic-atmospheric.com

"Leverkusen" descent to Frankfurt (Main) on 2008-03-27

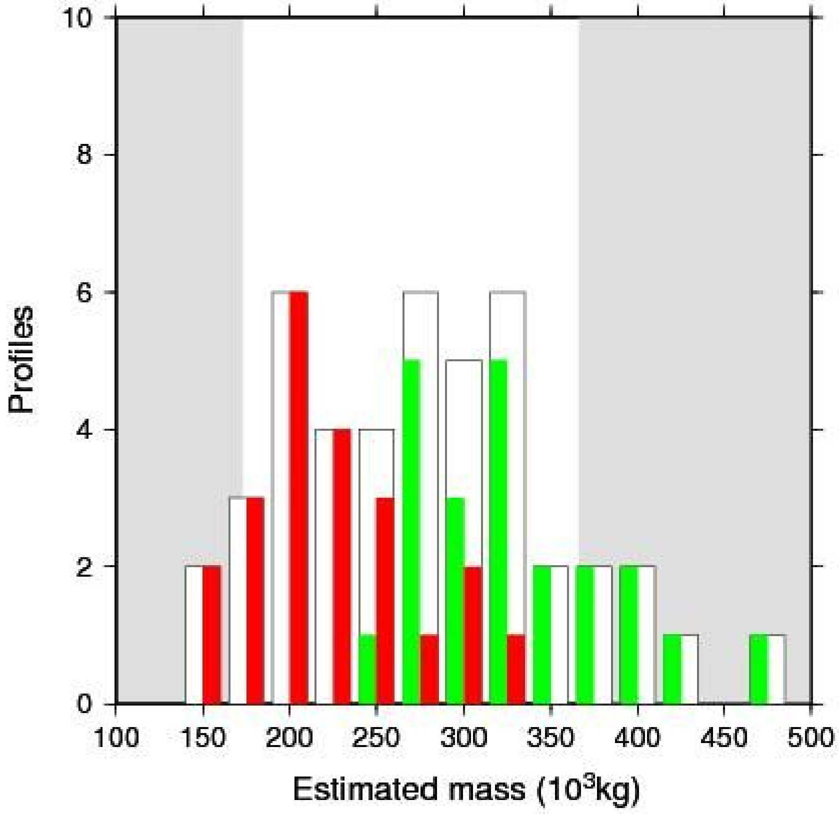
Validation





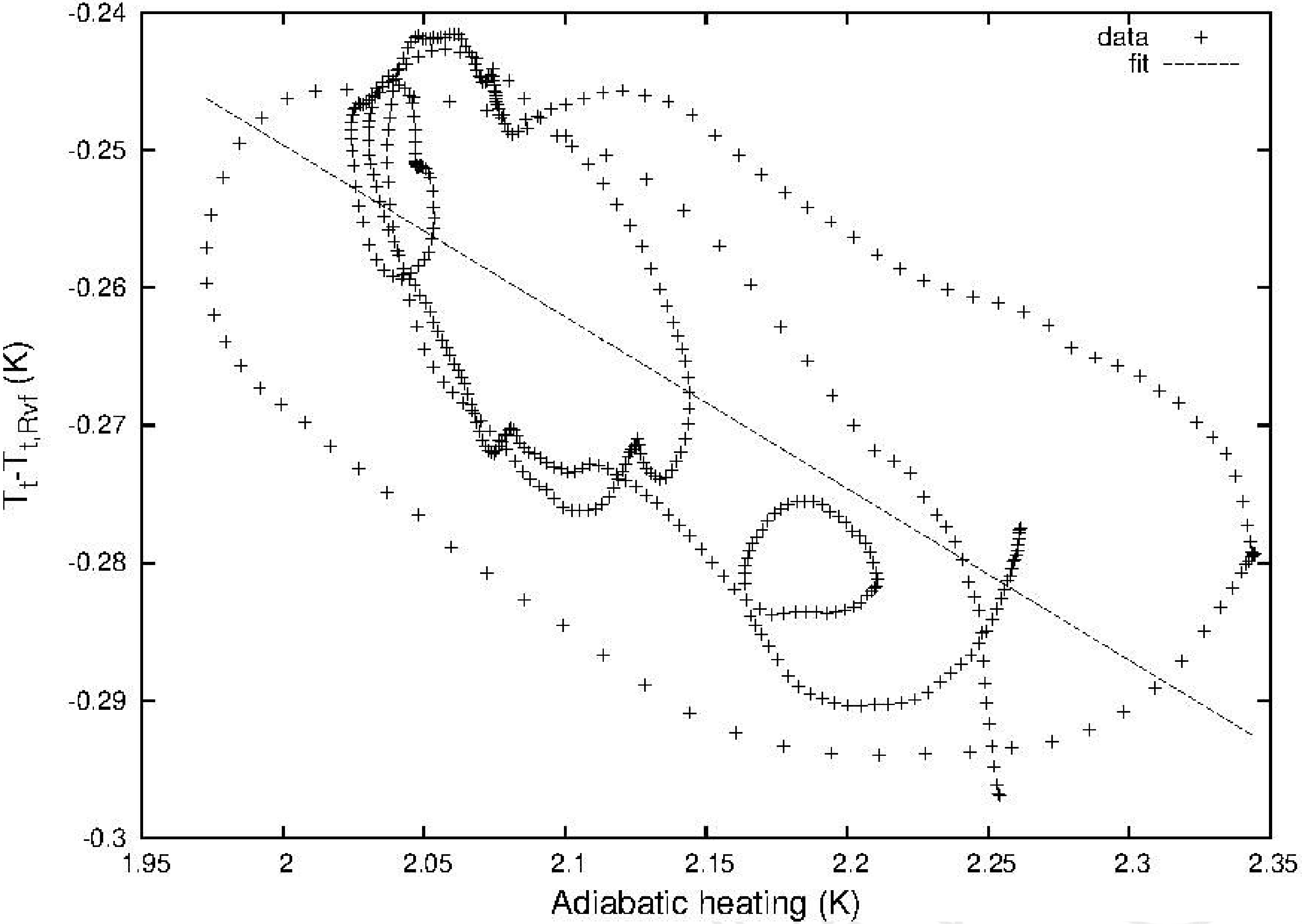
Validation resluts

- **Very good:**
  - Heading, Pitch, 3D-speed
- **Fair:**
  - Aircraft mass



Value	(unit)	intercept	slope	r^2
True heading	°	2.60	0.850	0.72
Pitch	°	-0.28	0.943	0.65
Roll	°	0.03	0.238	0.08
Angle of attack	°	1.01	0.655	0.15
w	ms^{-1}	0.35	0.965	0.94
v_{as}	ms^{-1}	1.28	0.943	0.68
v_{gs}	ms^{-1}	18.1	0.881	0.79

Example: Regression p,TAS vs T-offset

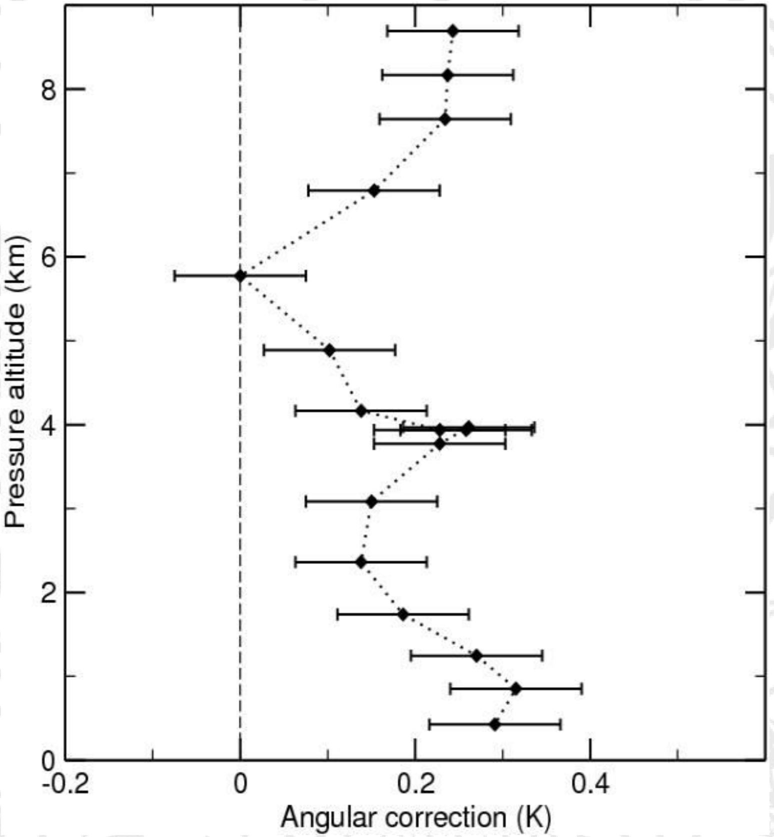


Conclusions

- **Trajectory reconstruction**
  - Physically consistent
  - Flight dynamic retrievable
  - Moderate computational costs

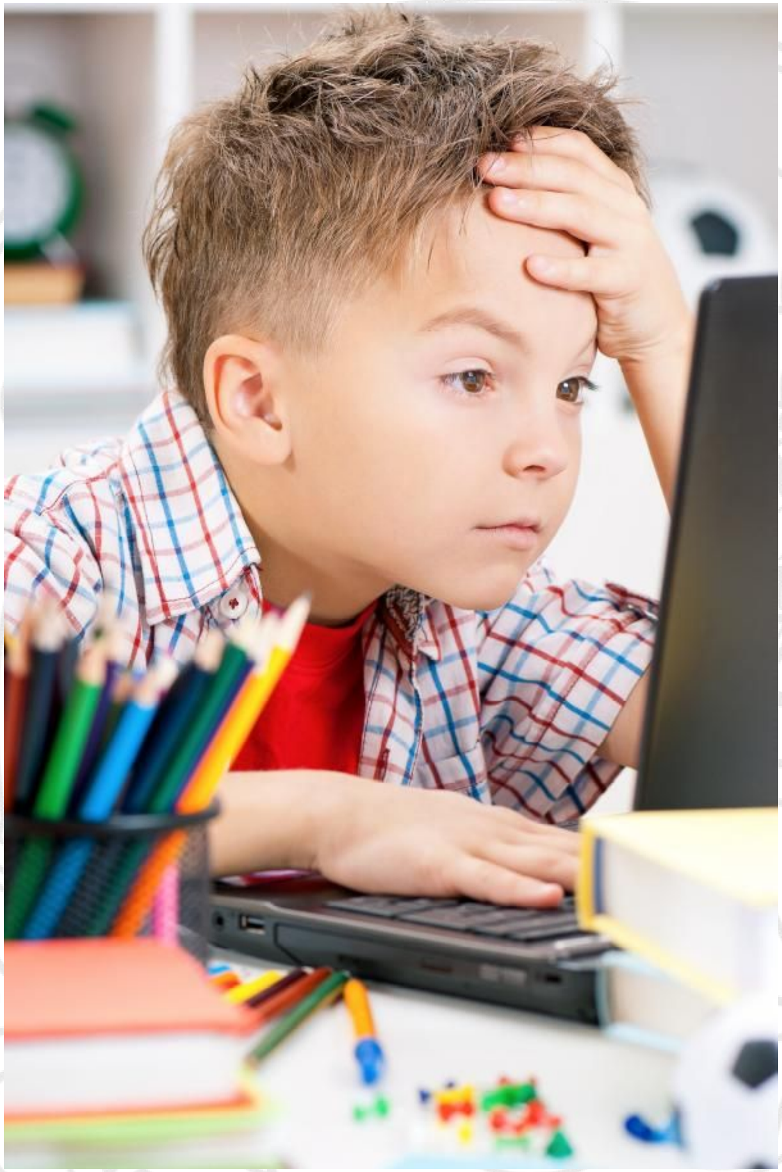
- **Validation**
  - DLH A340-600 and DLR Learjet
  - Very good for most variables
    - Large scatter for roll and angle of attack
  - Mean agreement reasonable

- **Valid candidate for error modeling**



Outlook

- **Statistical model**
  - errors as function of flight state
  - major component analysis
- **Feasibility of ADS-B**
  - for wind measurement without Mode-S radar position data
  - for developing countries
- **Need for graduants**
  - increasingly (!) deterred by required programming



www.colorbox.de

Thank you!
Questions?

References

Drüe, Frey, Hoff, Hauf (2008): "Aircraft type-specific errors in AMDAR weather reports from commercial aircraft" Quarterly Journal of the Royal Meteorological Society, **134**, 229-239, doi: 10.1002/qj.205

Drüe, Hauf and Hoff (2011): "Comparison of Boundary-Layer Profiles and Layer Detection by AMDAR and WTR/RASS at Frankfurt Airport" Boundary-Layer Meteorology, **135**, 407-432, doi: 10.1007/s10546-010-9485-0

Drüe, C. (2011): "Reconstruction of Aircraft Trajectories from AMDAR Weather Reports" J. Atmos. Oceanic Technol., **28**, 921-932, doi: 10.1175/2011JTECHA1499.1

Drüe and Heinemann (2013): "A Review and Practical Guide to In-Flight Calibration for Aircraft Turbulence Sensors" J. Atmos. Oceanic Technol., **30**, 2820-2837, doi: 10.1175/JTECH-D-12-00103.1

Drüe, Deimel and Hoff (2013): "A low-cost approach to derive upper-air wind measurements from ADS-B" EMS Annual Meeting 20013 (13th EMS / 11th ECAM), Reading, UK

Haering, Edward A. Jr. (1995): "Airdata Measurementand Calibration", NASA Technical Memorandum 104316, National Aeronautics and Space Administration (NASA) Dryden Flight Research Center, Edwards, CA, USA.

Palacios, F. et al. (2014): "Stanford University Unstructured (SU2): Analysis and Design Technology for Turbulent Flows." 52nd AIAA Aerospace Sciences Meeting - AIAA Science and Technology Forum and Exposition, SciTech 2014, doi: 10.2514/6.2014-0243.