Landing Attitude Analysis

Lukas Höhndorf

EASA SAFE 2019

Institute of
Flight System Dynamics

Agenda

- Motivation
- Data Preprocessing (see our presentation at EOFDM 2016)
  - Landing Reconstruction
  - Touchdown Point Detection
- Landing Attitude Analysis
- Summary

Motivation

Photo: © Juan De La Garza

Photo: © Lars Tretau

Photo: ©Thomas Luethi

Not only incidents but also the regular operation and their margins to an Abnormal Runway Contact (ARC) shall be analyzed.

Landing Reconstruction

- Recorded data always contain errors and uncertainties!
- Bad quality of data can prevent a proper landing attitude analysis
- Often, the sampling rate of position data is low

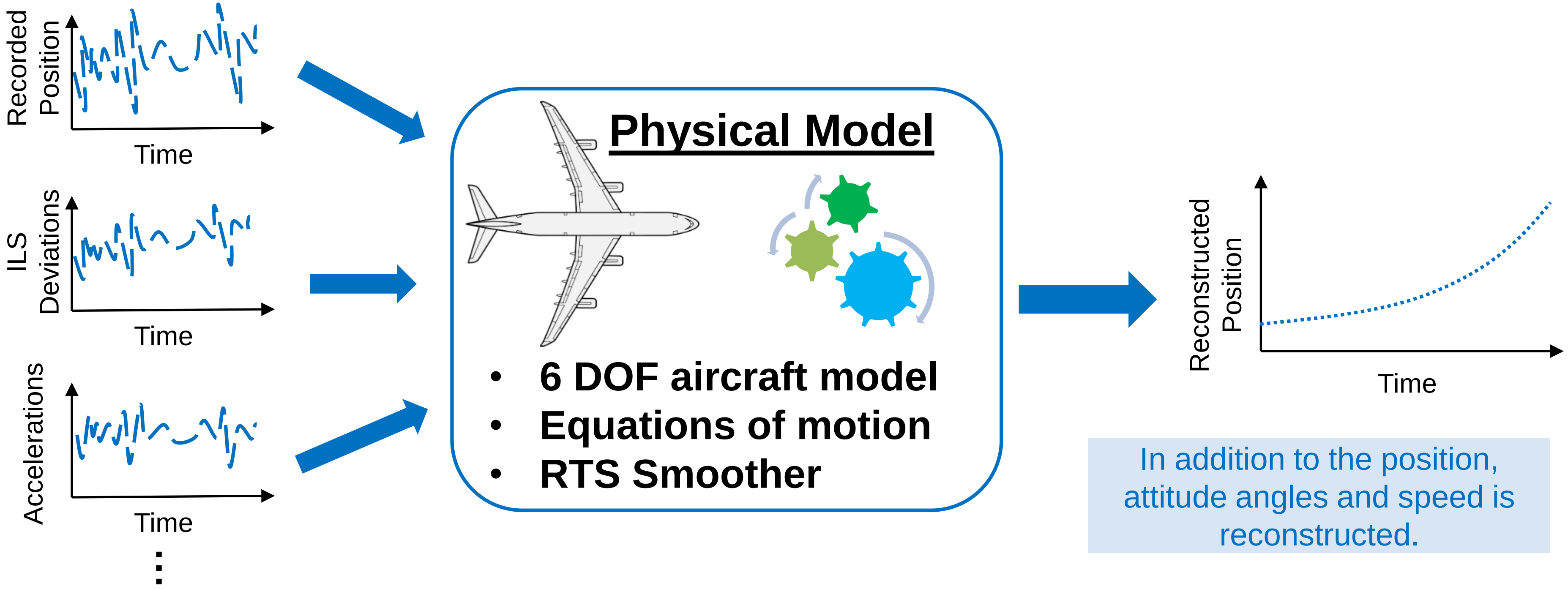
1.) Improve trajectory
- Increase sampling rate
- Reduce influence of data recording errors
- Physically more meaningful trajectory

2.) Correct lateral offset

3.) Correct longitudinal offset

Landing Reconstruction

Mathematical Method: State Estimation using Rauch-Tung-Striebel (RTS) Smoother



In addition to the position, attitude angles and speed is reconstructed.

The RTS Smoother is an advanced Kalman Filter that is already used in modern aircraft for navigation purposes.

Advantage of (offline) FDM compared to online application in the cockpit: Past AND FUTURE data recordings can be taken into account!

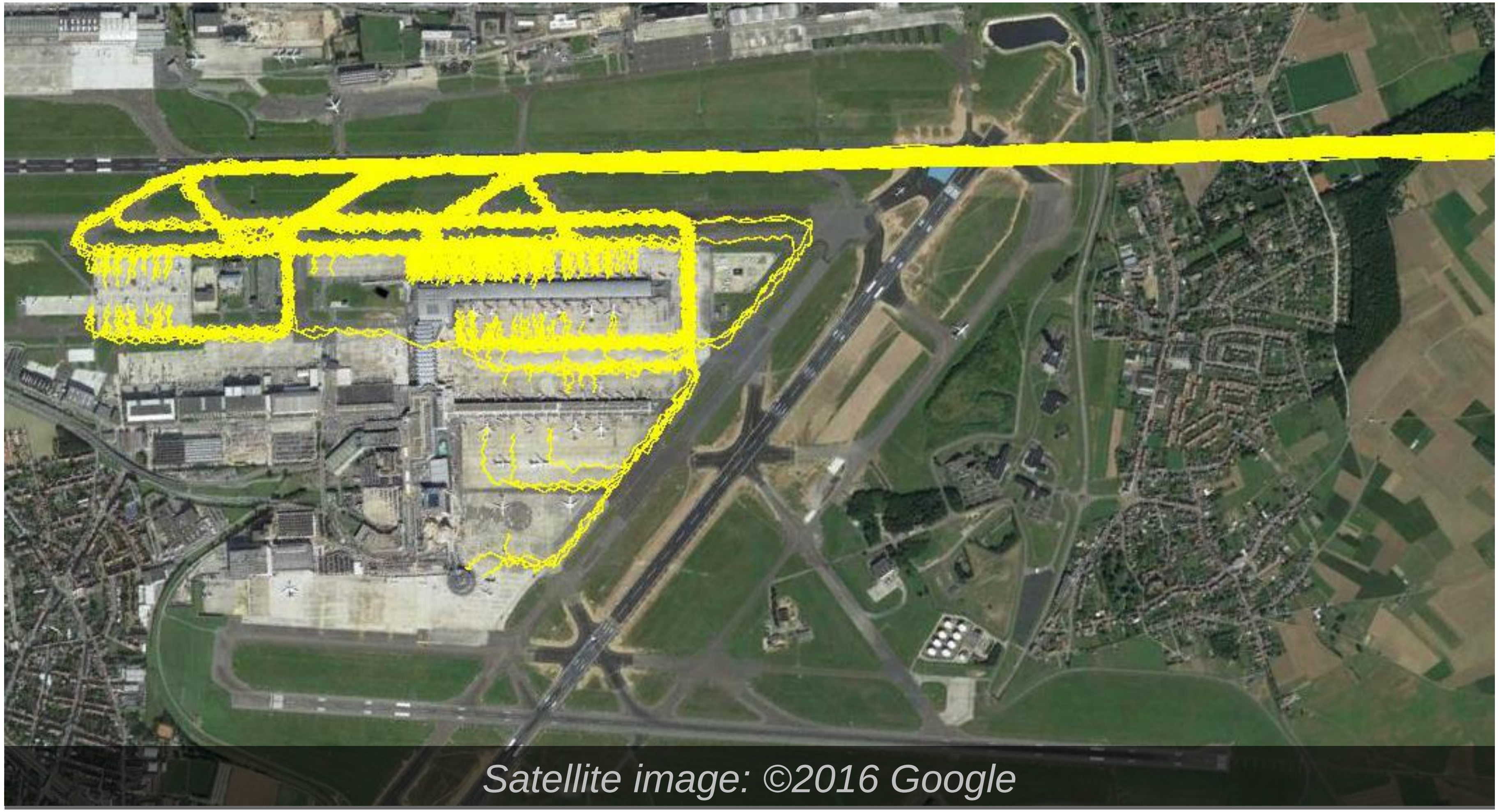
Landing Reconstruction

After Reconstruction, the following aircraft states will be available with increased quality and in full sampling rate (8Hz)

- Aircraft Position
  - latitude/longitude
  - x/y/z-position in local runway frame
  - radio altitude
  - barometric altitude
  - WGS84-altitude
- Aircraft Kinematic Velocity
  - groundspeed
  - vertical speed
  - track angle (true track)
  - velocity components in body fixed frame
- Aircraft Aerodynamic States
  - TAS
  - angle of attack
- Aircraft Attitude
  - pitch/bank/yaw
- Aircraft Rotation Rates
  - pitch rate/roll rate/yaw rate
- Wind Reconstruction
  - horizontal wind (speed and wind angle)
  - vertical wind

Landing Reconstruction

Raw GPS trajectories



Landing Reconstruction

Reconstructed trajectories

Touchdown Point Detection

Angle of Attack

Pitch Rate

Elevator Deflection

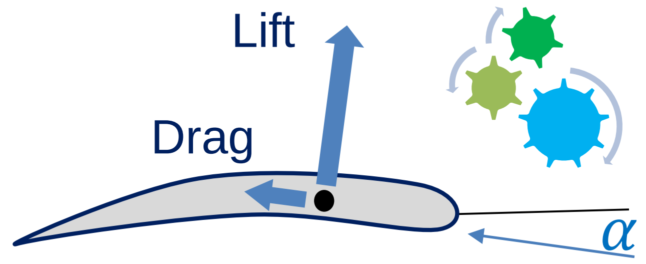
Stabilizer Position

Spoiler Deflection

Engine RPM

Physical Model for Force Coefficients

$C_{z,model}$ & $C_{x,model}$



Model Based Force Coefficients

$C_{z,model}$ & $C_{x,model}$

Model DOES NOT include acceleration caused by ground reaction force

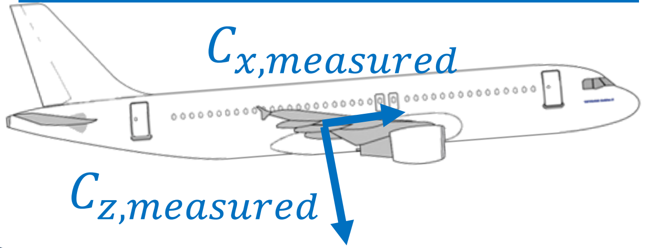
---

Vertical Acceleration

Longitudinal Acceleration

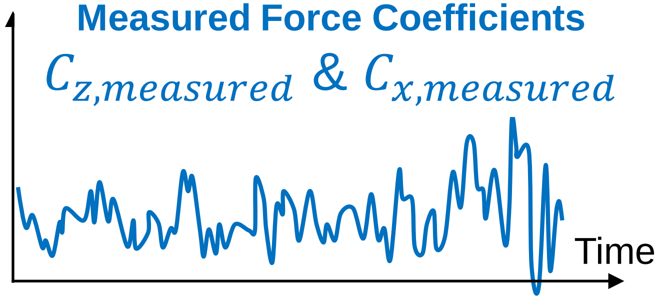
Measured Force Coefficients

$C_{z,measured}$ & $C_{x,measured}$



Measured Force Coefficients

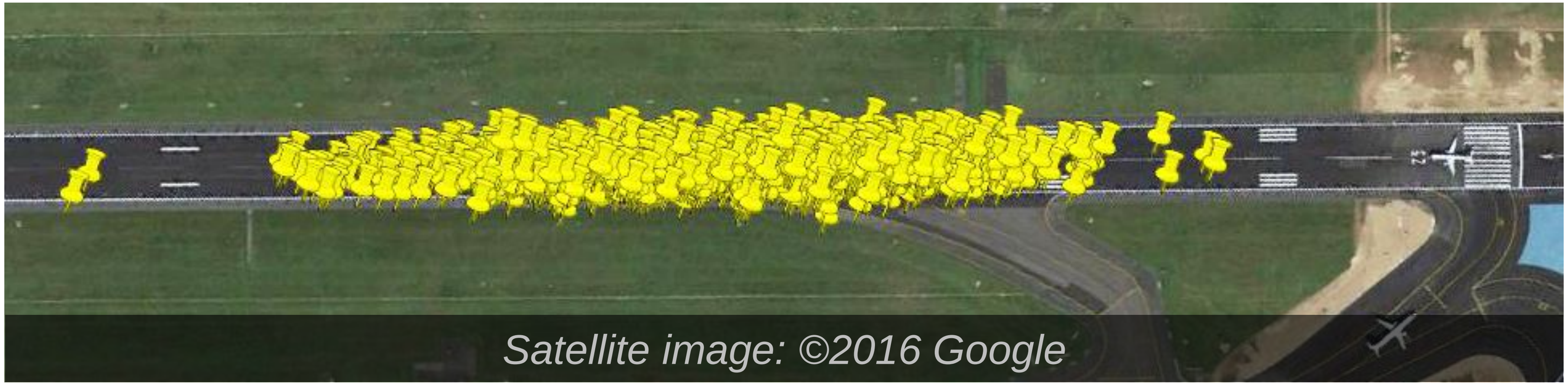
$C_{z,measured}$ & $C_{x,measured}$



Measurement DOES include acceleration caused by ground reaction force

Touchdown Point Detection

Raw GPS touchdown locations



Reconstructed touchdown locations

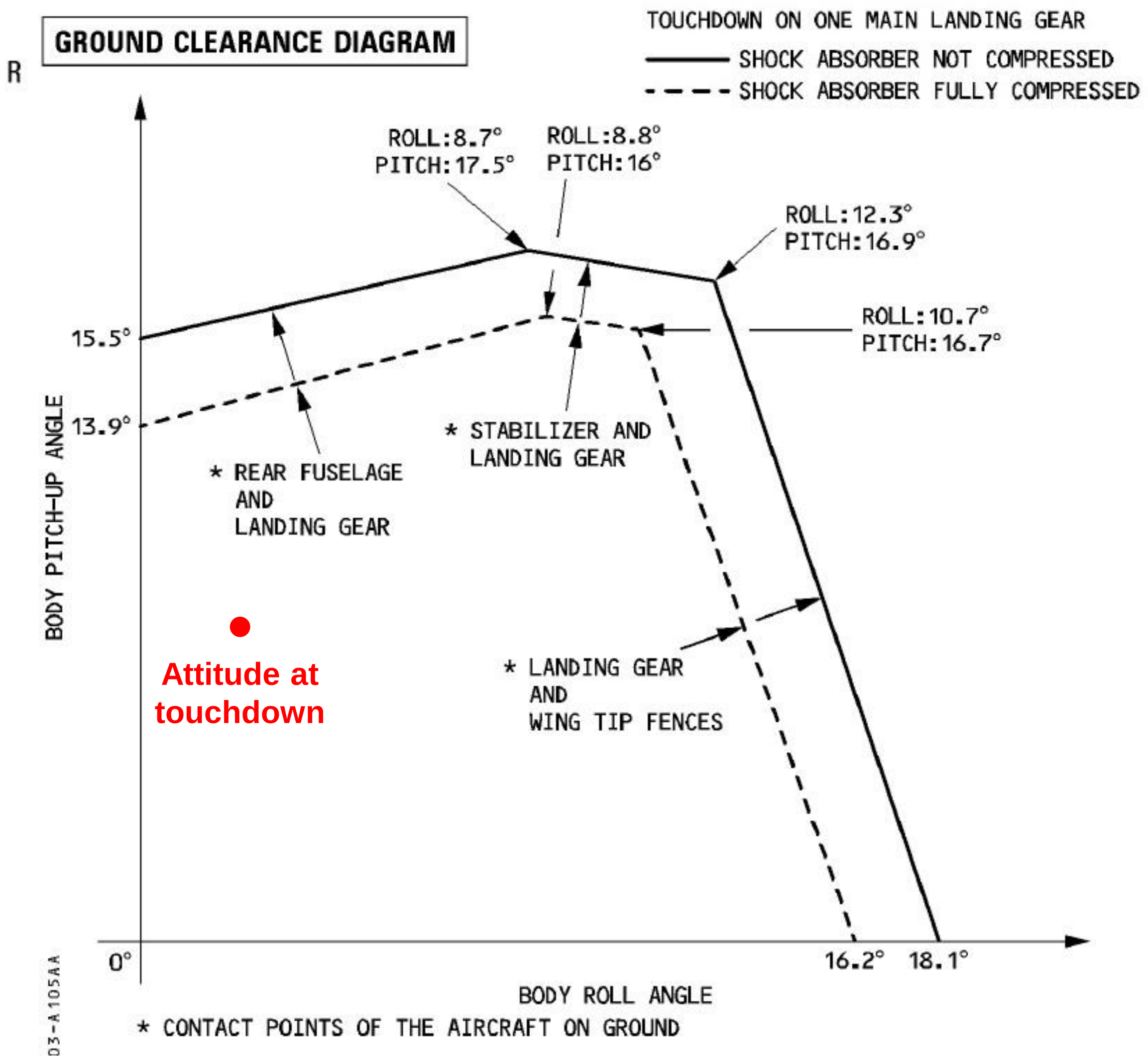
Landing Attitude Analysis

Based on an idea of Brussels Airlines:

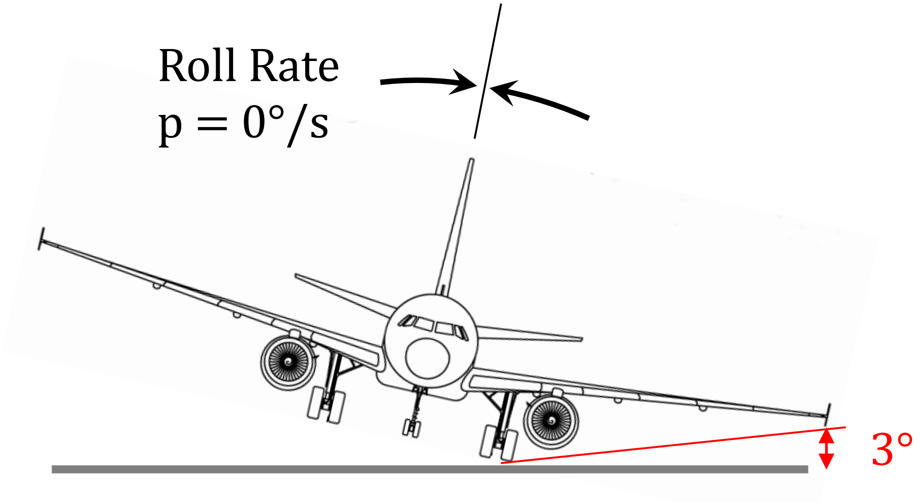
<u>For a specific flight:</u>
How great is the margin at touchdown for

a) Any abnormal runway contact
b) Tail Strike
c) Wingtip Strike
d) Stabilizer Strike

?



Landing Attitude Analysis



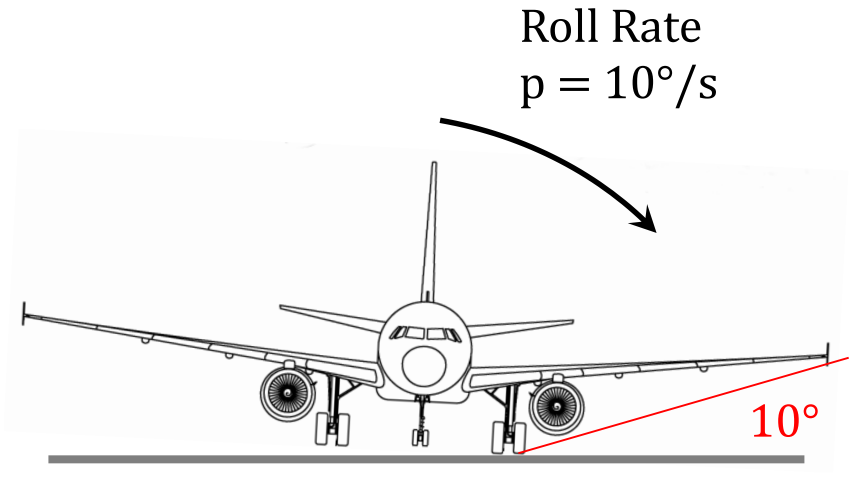
Dangerous situation due to high static bank

Angle Margin μ

Angle between horizontal plane and vector from main gear to critical point

$$\mu = 3°$$

$$\tau = \frac{\mu}{\dot{\mu}} \approx \frac{3°}{0°/s} = \infty$$



Dangerous situation due to rotational dynamics

Time Margin τ

Time to ground contact of critical point if current rotation rates are kept

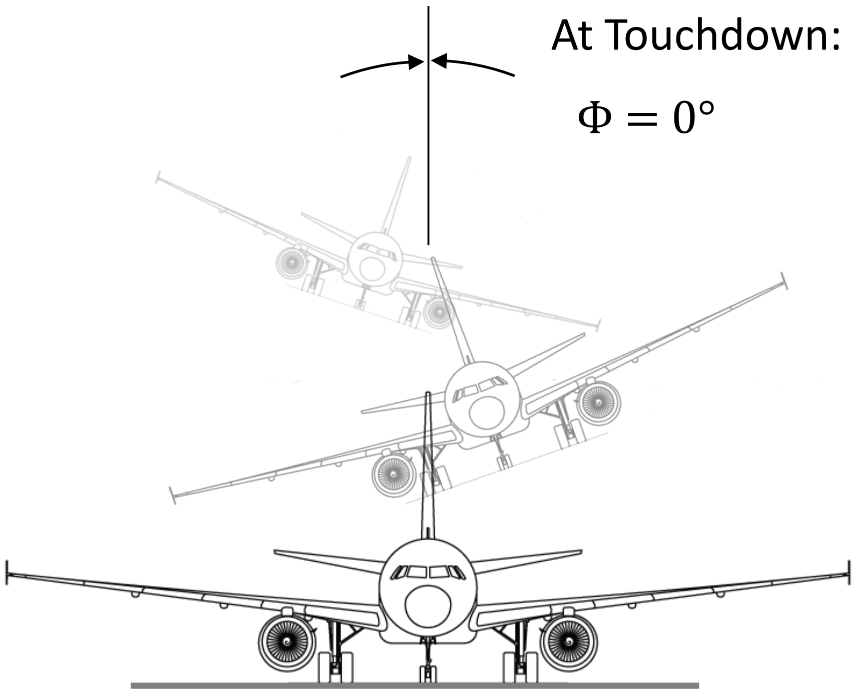
$$\mu = 10°$$

$$\tau = \frac{\mu}{\dot{\mu}} \approx \frac{10°}{10°/s} = 1s$$

→ Quantify Margin as Angle Margin AND Time Margin

Institute of
Flight System Dynamics

Landing Attitude Analysis



Safe touchdown but unstable attitude beforehand

→ Quantify Margin at touchdown AND minimum margin during landing

Angle Margin at Touchdown	Minimum Angle Margin During Landing*
Time Margin at Touchdown	Minimum Time Margin During Landing*

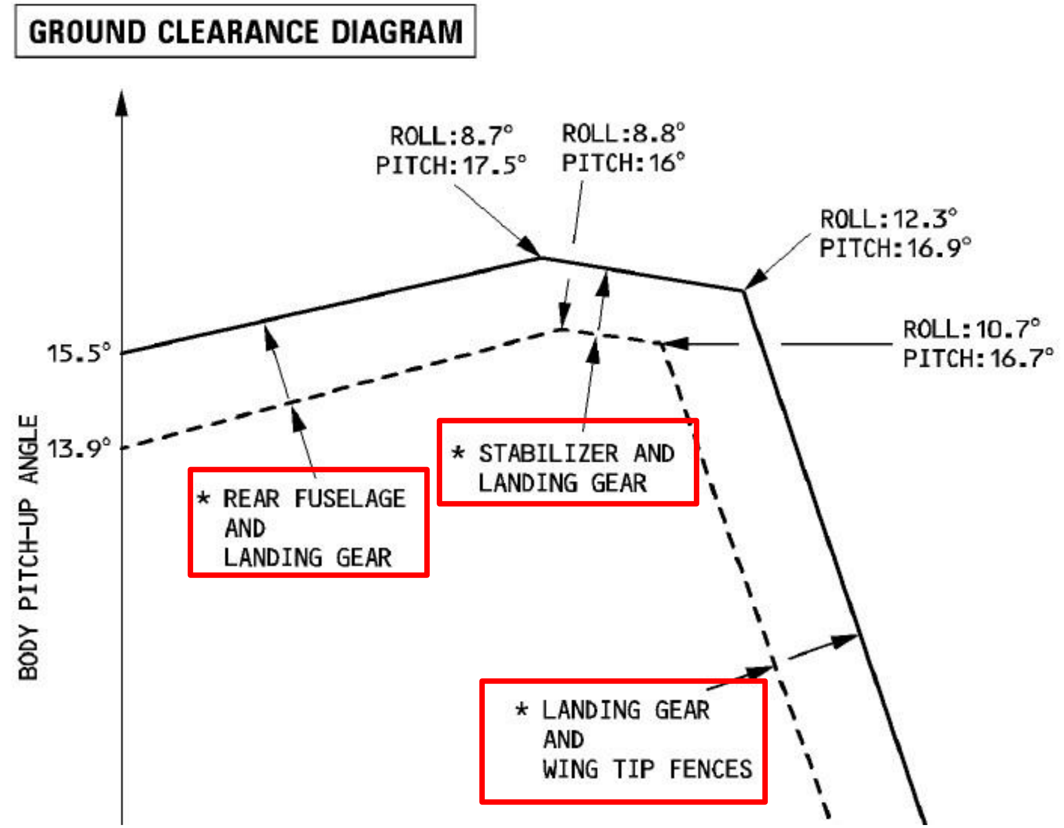
*Landing: 100ft Radio Altitude until 5 seconds after touchdown

4 metrics to assess landing attitude margin

Landing Attitude Analysis

1) **Determine Critical Points** P_{Crit}

→ For A319: Tail, Wingtips, Stabilizer Edges (from Ground Clearance Diagram)



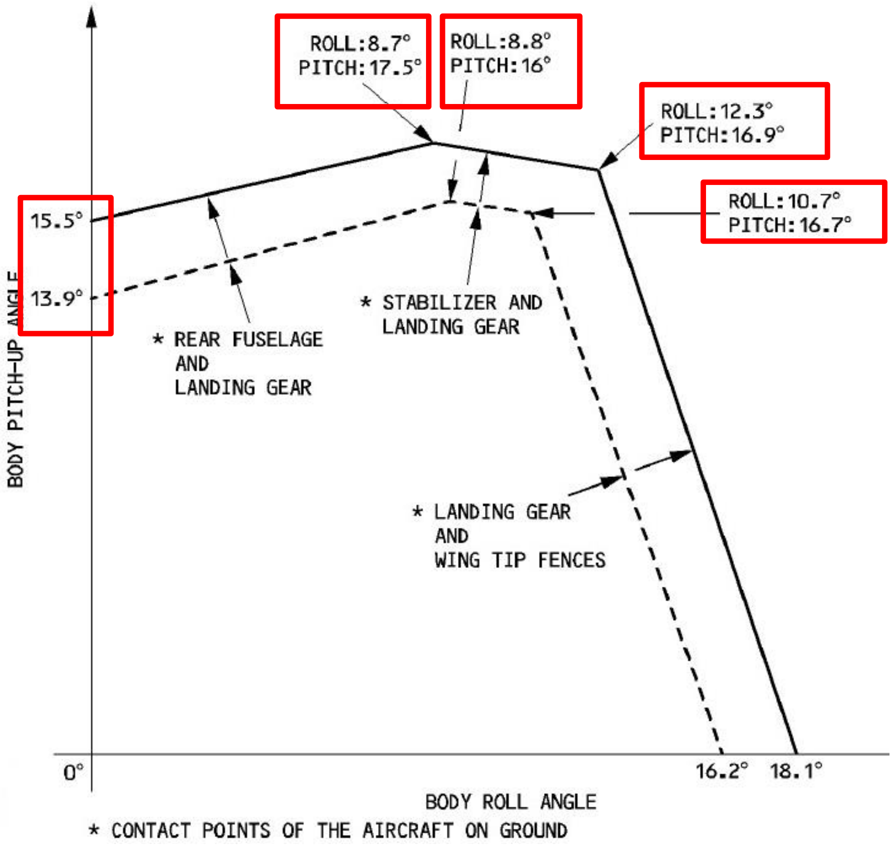
Institute of Flight System Dynamics

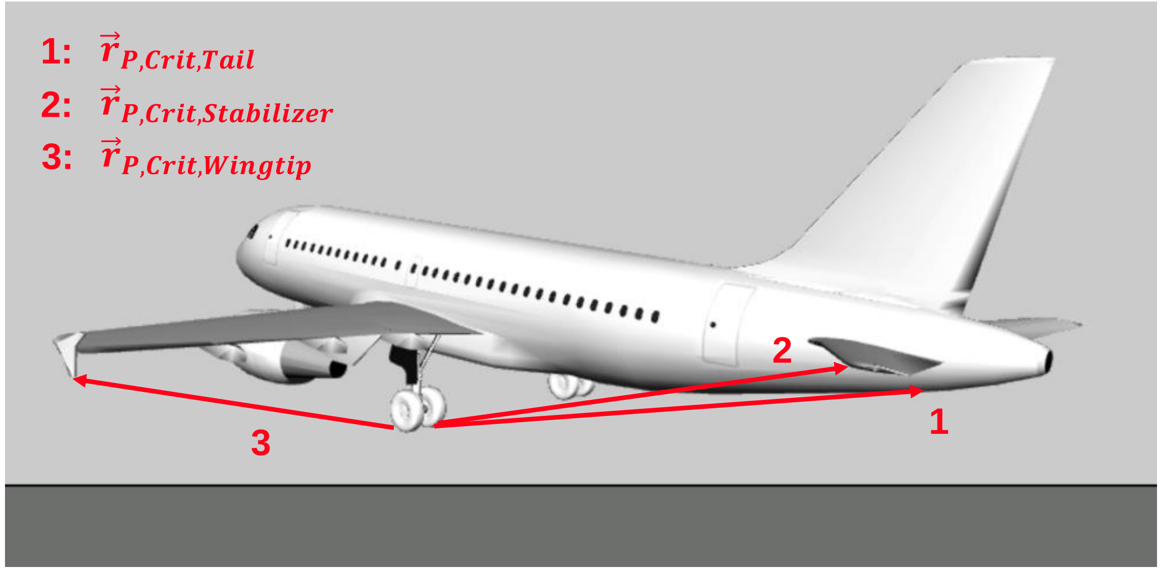
Landing Attitude Analysis

2) Determine Vectors from Main Gear Wheel to Critical Points $\vec{r}_{P,Crit}$

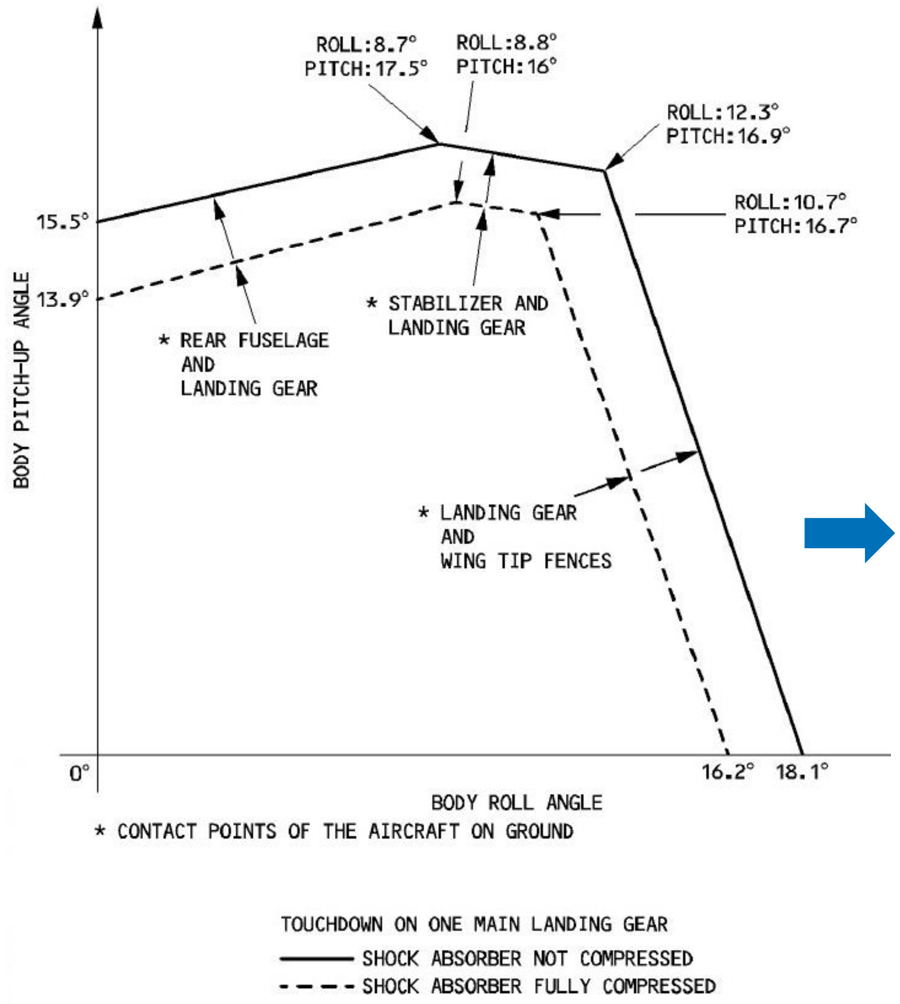
→ "Reverse Engineering"

Infer values from the given roll and pitch angles in ground clearance diagram



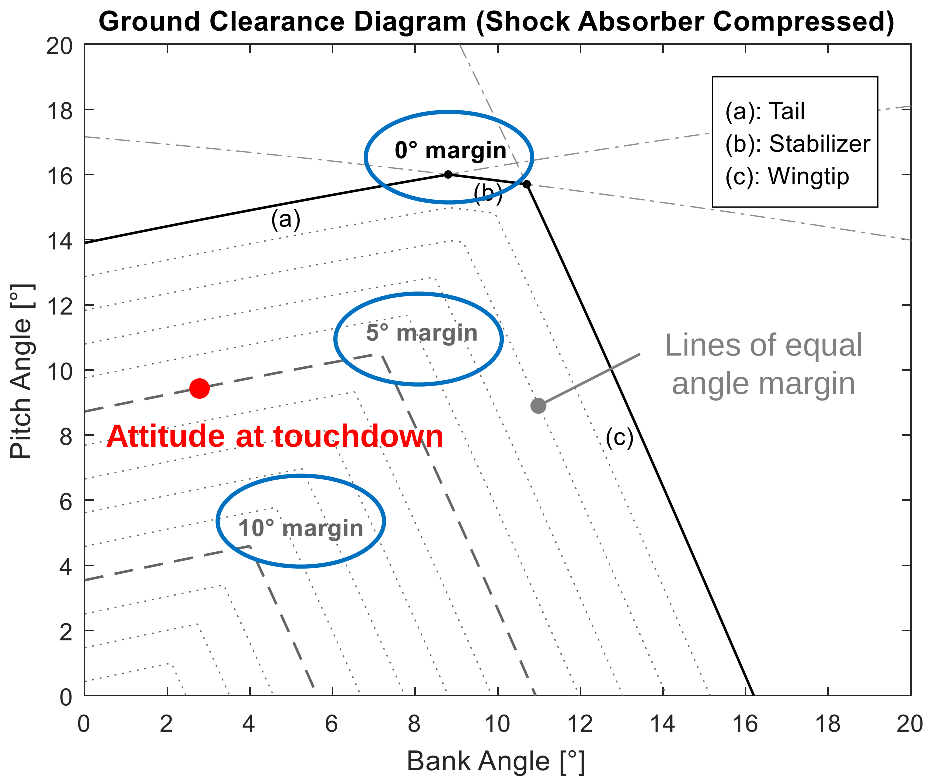


Landing Attitude Analysis



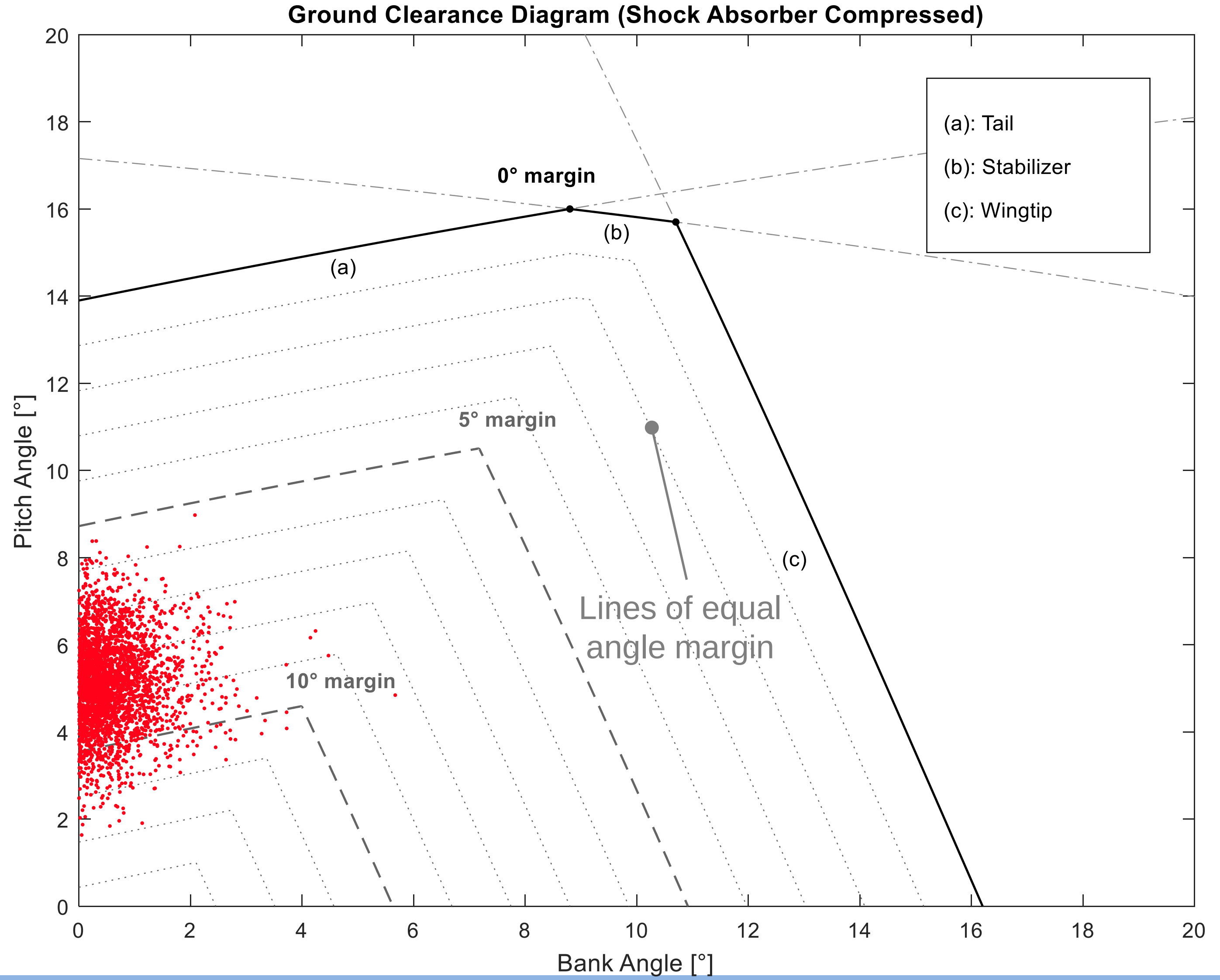
Reproduced Ground Clearance Diagram
(based on the concept of angle margin)

Exemplary for shock absorbers fully compressed



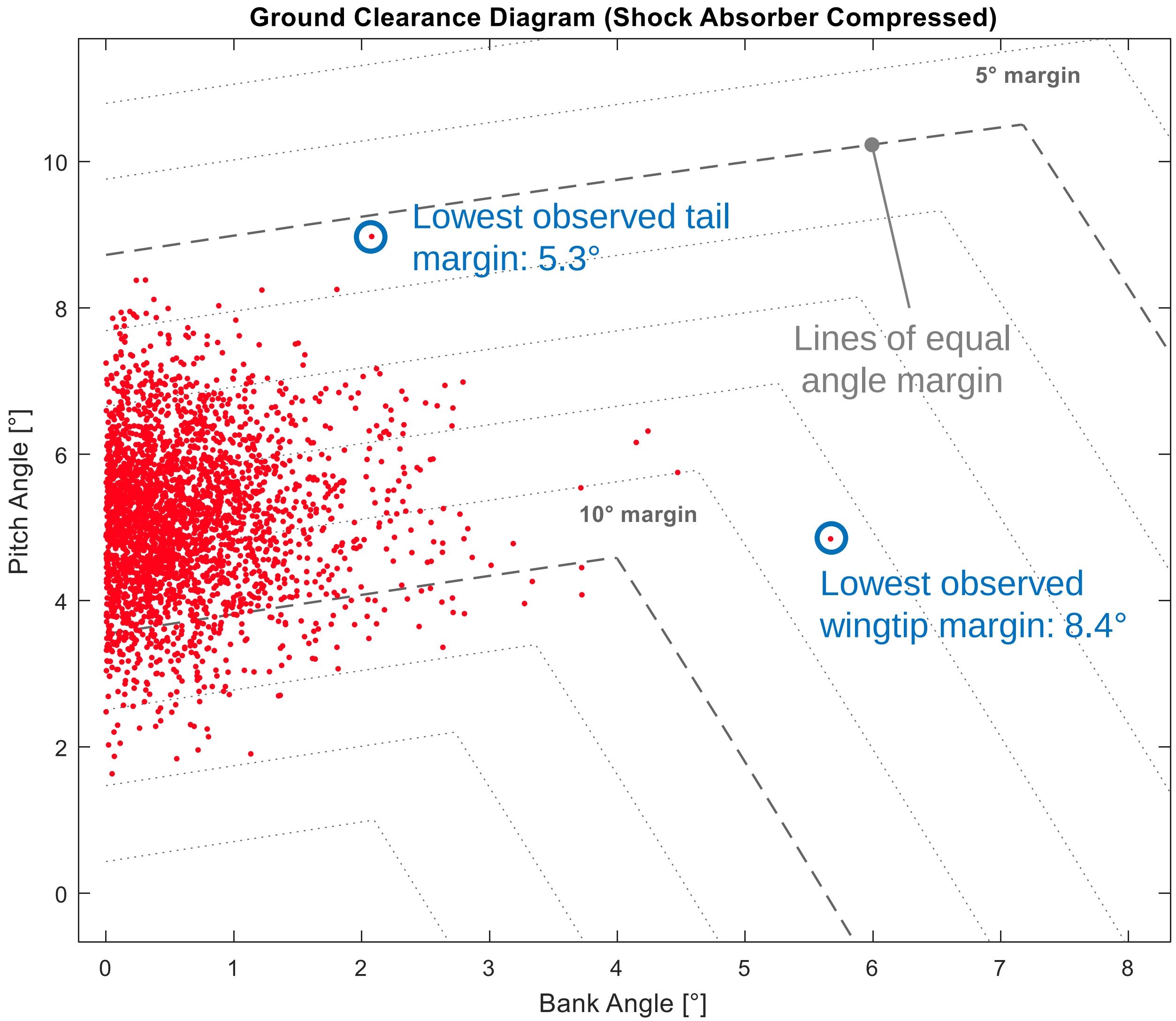
→ Margin to abnormal runway contact can now be quantified: ~ 5° angle margin

Landing Attitude Analysis

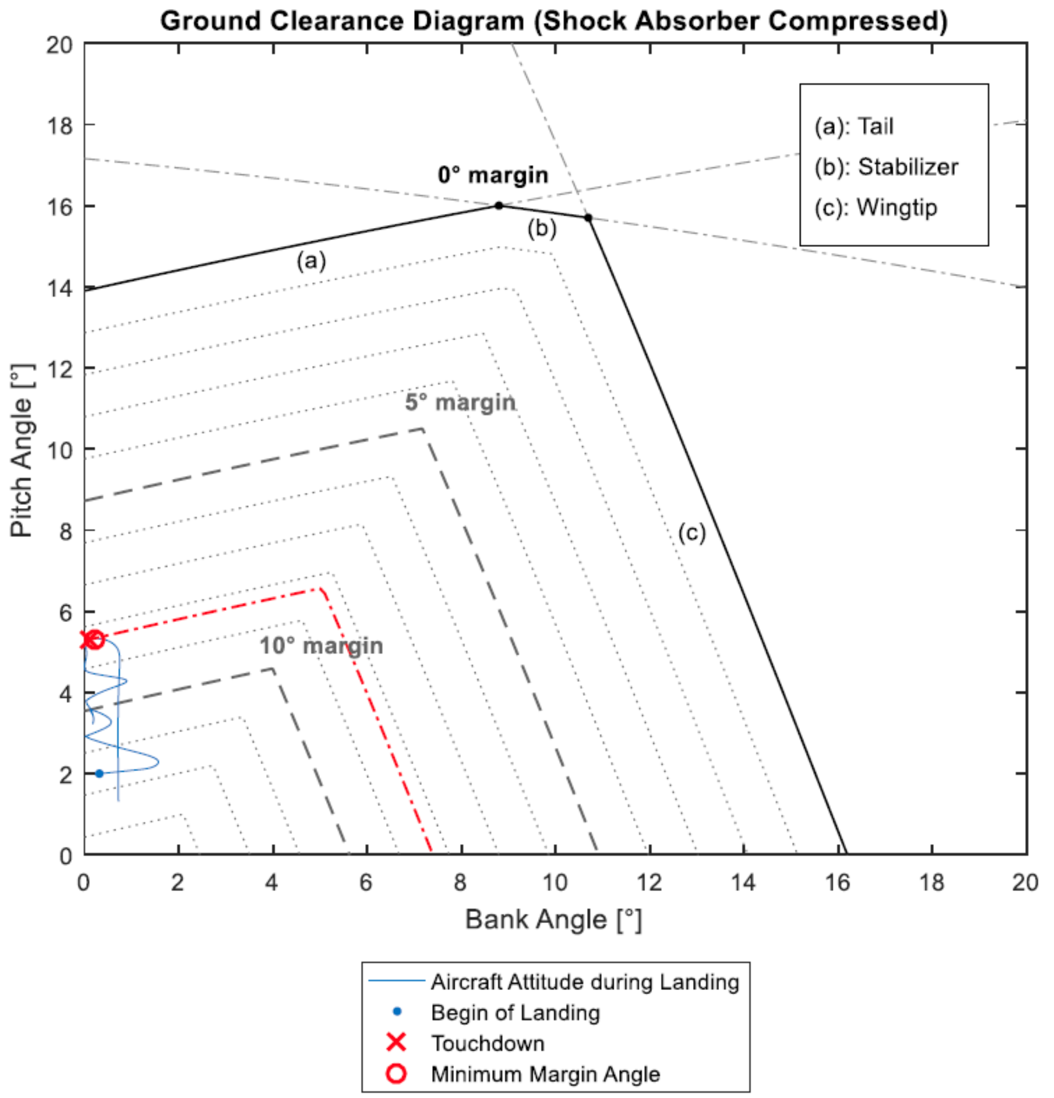


Institute of
Flight System Dynamics

Landing Attitude Analysis

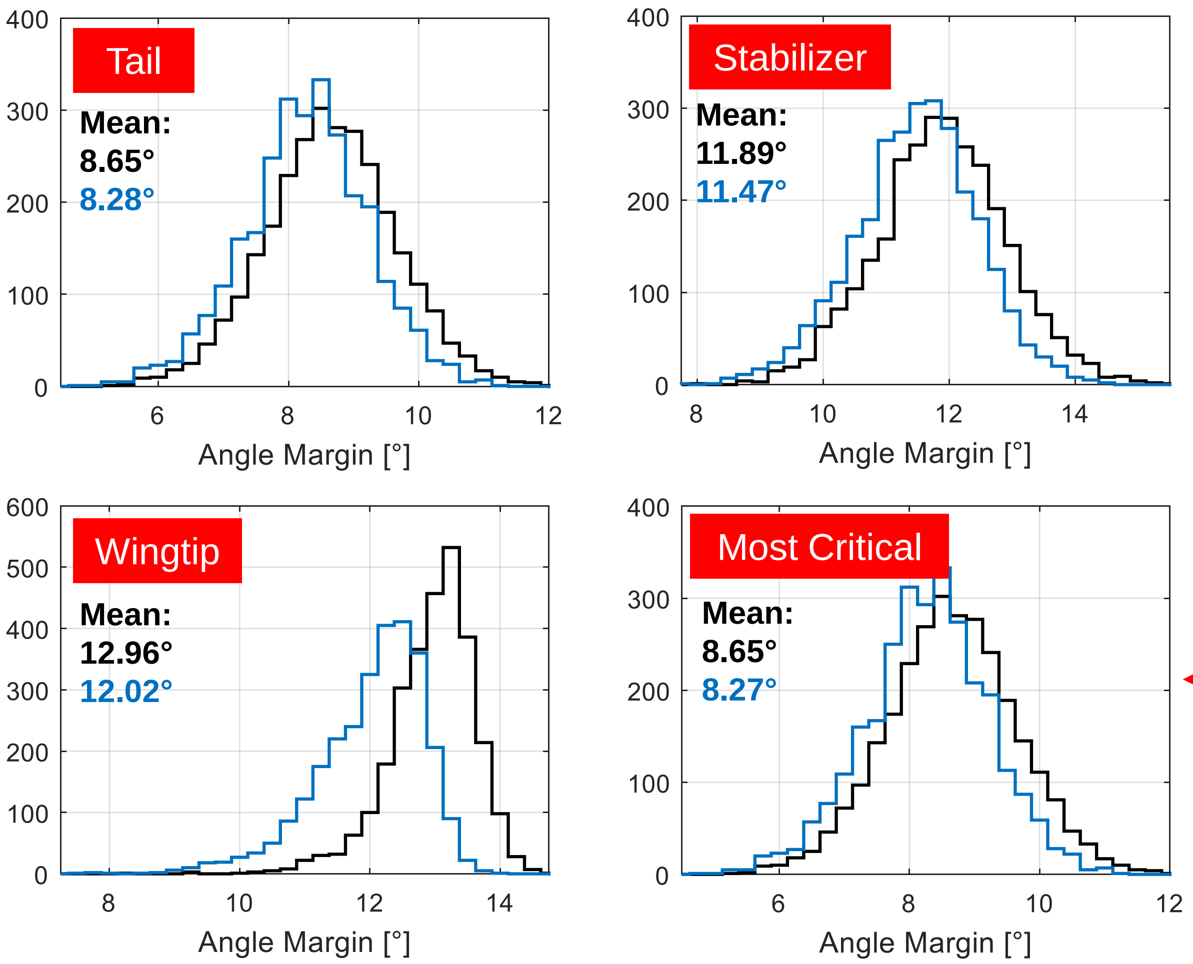


Landing Attitude Analysis



Landing Attitude Analysis

- *Angle Margin at Touchdown*
- *Minimum Angle Margin During Landing*



First Conclusions:

- Lowest angle margins are generally observed for aircraft tail
- Tail angle margin is most critical in 99.7% of all landings

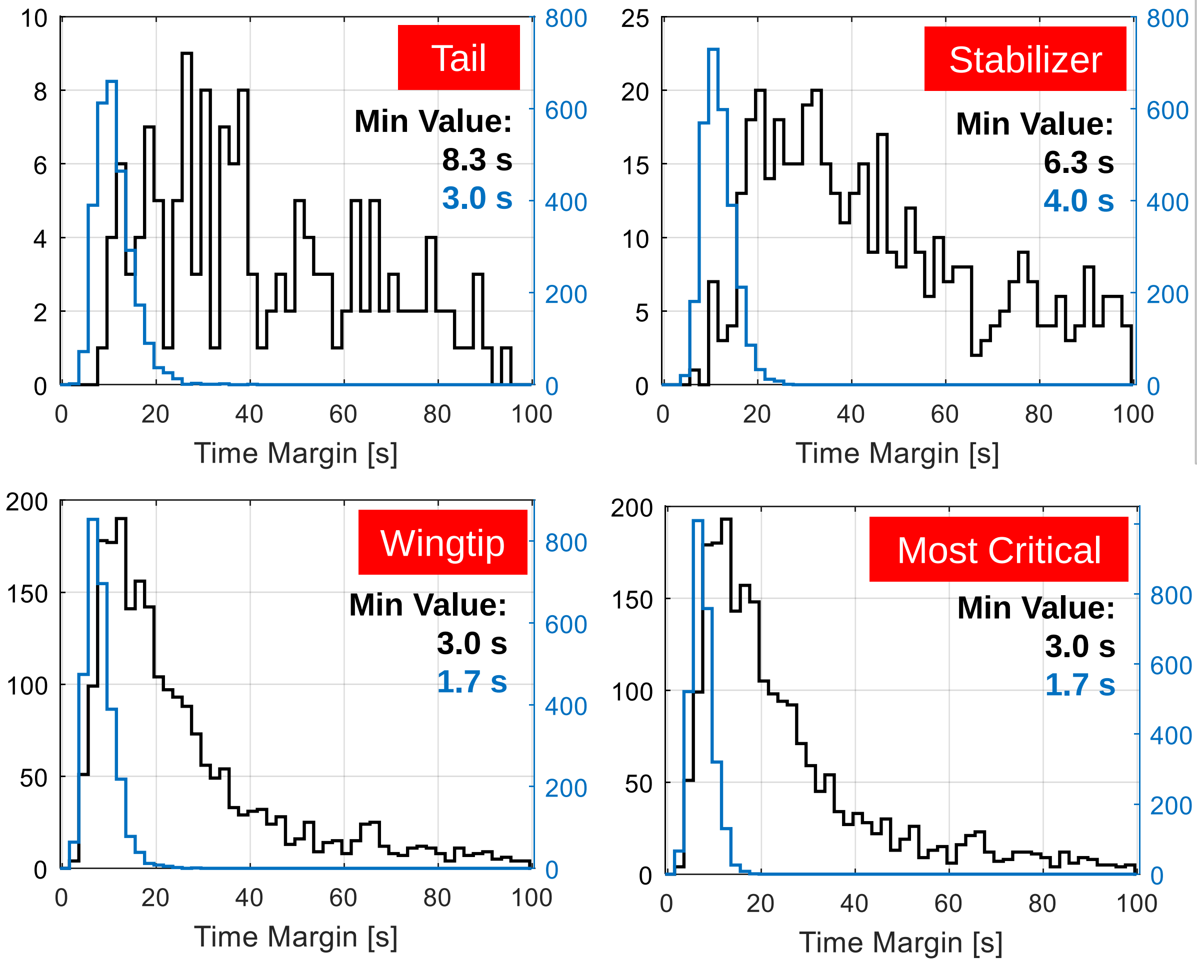
→ In static & stable conditions, by far the greatest risk is associated with tail strike

Most Critical Angle Margin

Tail:	2830 flights (99.7%)
Stabilizer:	0 flights (0%)
Wingtip:	9 flights (0.3%)

Landing Attitude Analysis

- *Time Margin at Touchdown*
- *Minimum Time Margin During Landing*



First Conclusions:

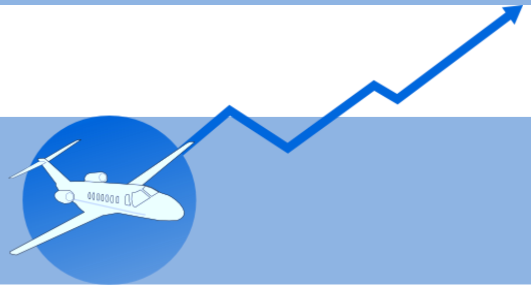
- Lowest time margins are generally observed for aircraft wingtip
- Wingtip time margin is most critical in 75.0% of all landings

→ In conditions with high rotational dynamics, greatest risk is associated with wing strike

Most Critical Time Margin

Tail:	690 flights (24.3%)
Stabilizer:	20 flights (0.7%)
Wingtip:	2129 flights (75.0%)

Summary



Landing Attitude Analysis

Physically motivated smoothing of FDM data

Precise touchdown points detections

Landing Attitude Analysis

Quantification of abnormal runway contact margins

Airport and runway comparisons for abnormal runway contact risk

Institute of Flight System Dynamics

Source: Google Earth, 2016 DigitalGlobe

Institute of Flight System Dynamics
Technical University of Munich
Boltzmannstraße 15
85748 Garching bei München
Germany

Javensius Sembiring, javensius.sembiring@tum.de
Lukas Höhndorf, lukas.hoehndorf@tum.de
Xiaolong Wang, xiaolong.wang@tum.de
Florian Schwaiger, f.schwaiger@tum.de
Serçin Höhndorf, sercin.hoehndorf@tum.de
Lukas Beller, lukas.beller@tum.de

Joachim Siegel, joachim.siegel@t-online.de

Florian Holzapfel, florian.holzapfel@tum.de

Thanks to Brussels Airlines for the support in this project!

Thank you for your attention!