Landing Trajectory and Touchdown Point Reconstruction

EOFDM Conference 2016

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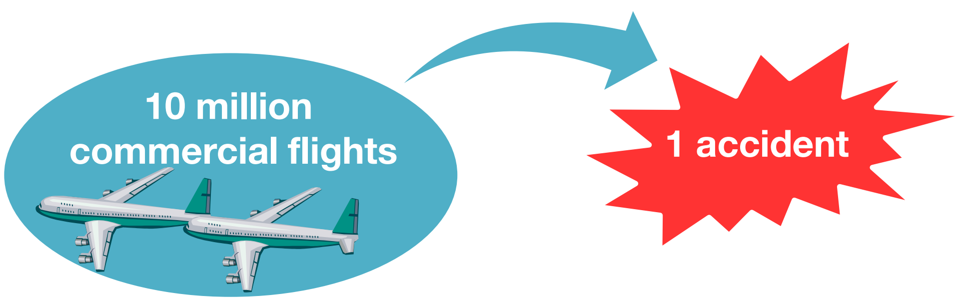
General Concept

ICAO DOC 9859

- Airlines are required to implement a safety management system (SMS)
- SMS requires operators also to define their own **Acceptable Level of Safety (ALoS).**

- **Europe** aims at less than one accident per ten million flights (i.e. **accident probability of 10^{-7} per flight**).



Flightpath 2050

Central question: What is the current safety level of my airline?

General Concept

$$P_{Accident} = \frac{Number\ of\ accidents}{Number\ of\ flights}$$

Classical statistical approach

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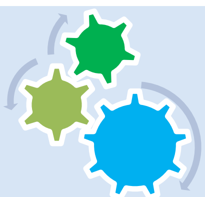
$$P_{Accident} = \frac{0}{400\,000} = 0$$

Runway overrun example



Developed Predictive Analysis
Making **quantitative statements** about the future state based on **previous experience and knowledge.**

Compare the presentations of Ludwig Drees and Javensius Sembiring (TUM-FSD) at the EOFDM Conference 2014

Problem Statement and Objective

- Recorded data always contain errors and uncertainties!
- Example: Bad quality of position data (if you consider them solely) can make a thorough touchdown analysis impossible
- Often, the sampling rate of position data is low

Compare the presentation "Landing trajectory computation" of Géraud de Rivals (Airbus) at EOFDM Conference 2014

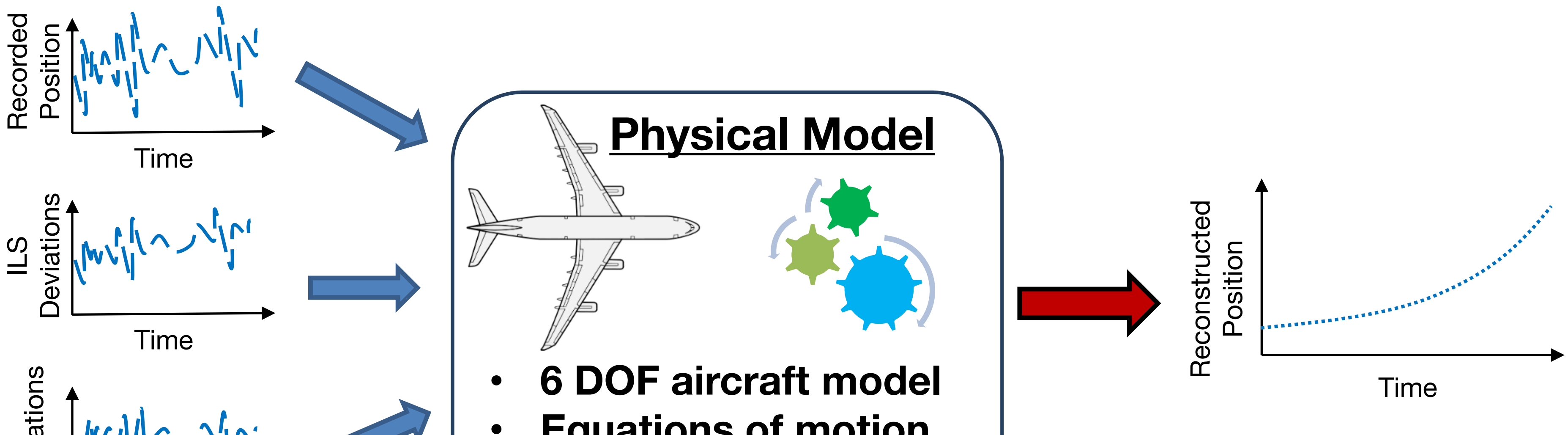
1.) Improve trajectory
- Increase sampling rate
- Reduce influence of data recording errors
- Physically more meaningful trajectory

2.) Correct lateral offset

3.) Correct longitudinal offset

Concept

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



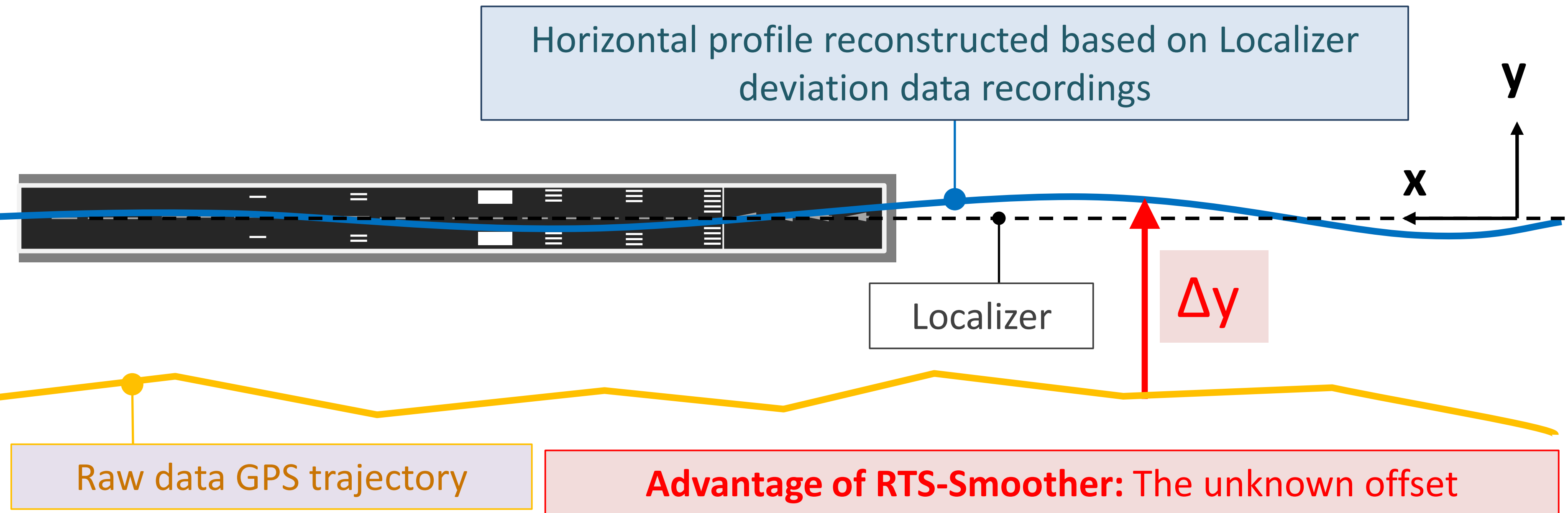
In addition to the position, attitude angles and speed is reconstructed.

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!

Correct Lateral Offset

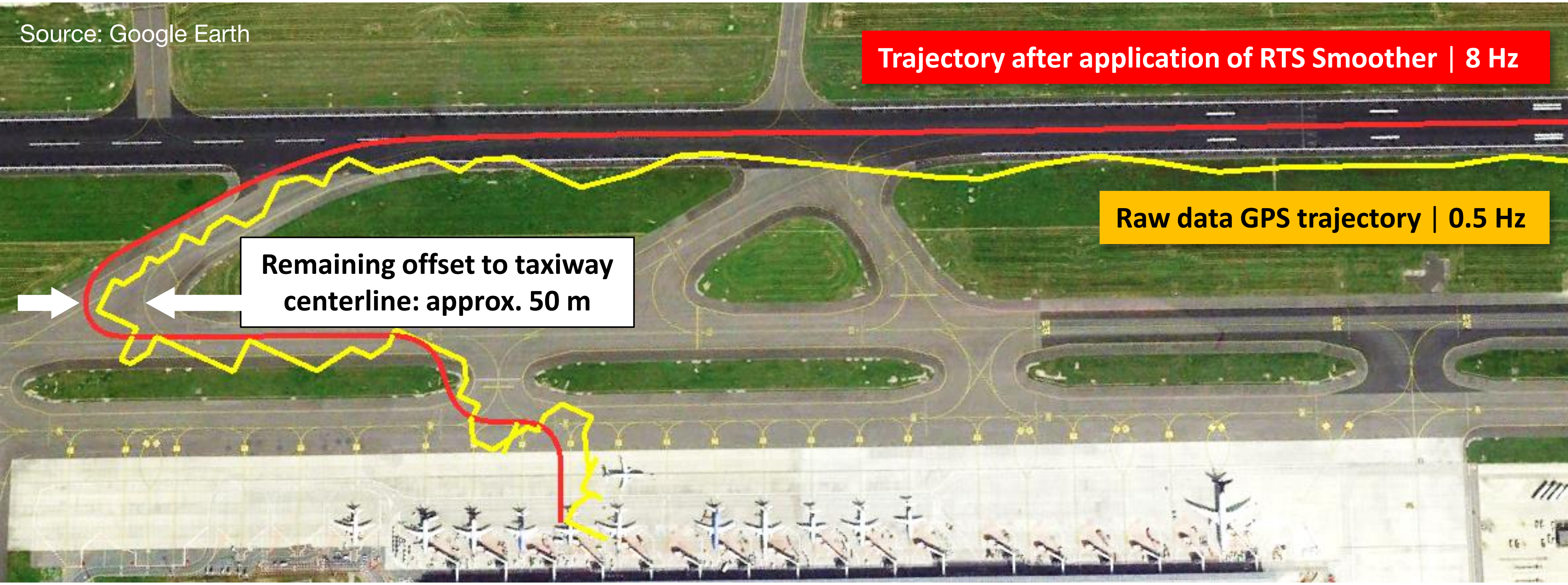
Mathematical Method: Estimate offset Δy by use of Localizer deviation data recordings



Advantage of RTS-Smoother: The unknown offset correction Δy can be estimated simultaneously with the system states.

Analogously for the Glideslope deviation and the longitudinal offset.

RTS Smoother Output



1.) Improve trajectory

- Increase sampling rate
- Reduce influence of data recording errors
- Physically more meaningful trajectory

2.) Correct lateral offset

3.) Correct longitudinal offset

Why?

RTS Smoother Output

3.) Correct longitudinal offset

Why is the achieved longitudinal offset correction worse than the lateral?

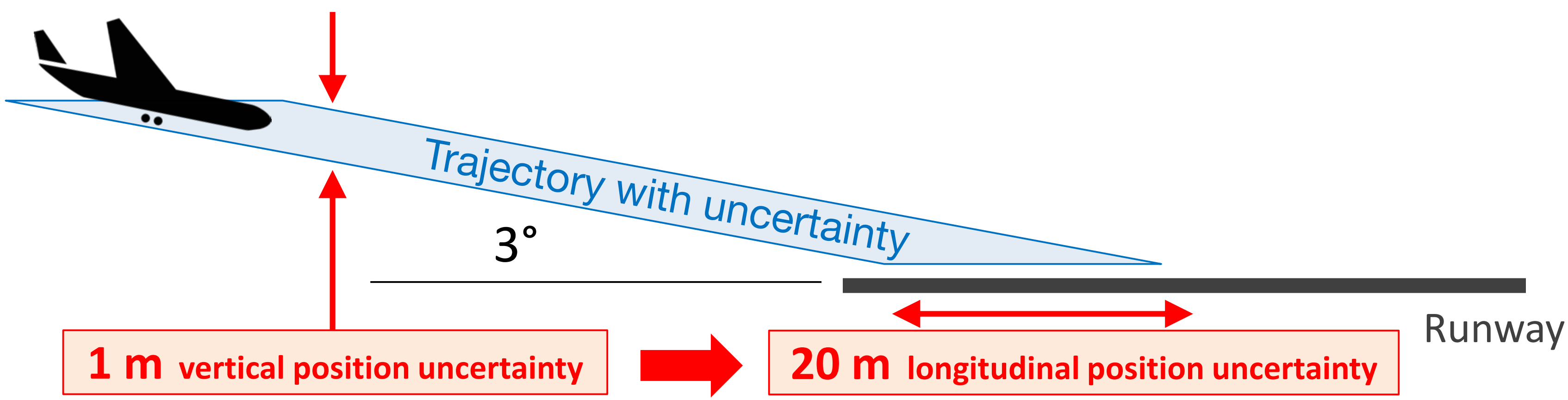
1) Precise reconstruction of altitude above threshold is difficult

- Combination of Radio Altitude, WGS 84 Altitude and Barometric Altitude
- Many corrections have to be applied

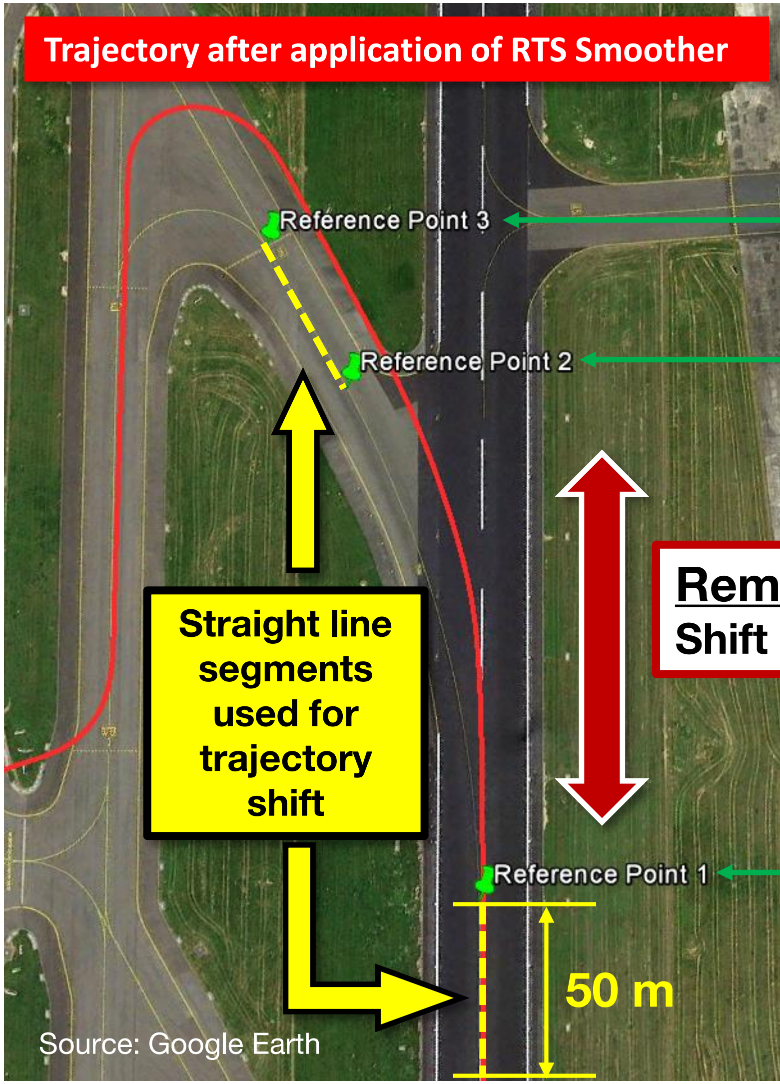
2) Imperfect knowledge of glide path intersection point

- Glide path antenna position is used instead

3) Strong error amplification due to small Glideslope angle



Longitudinal Shift Correction Based on Runway Exit



Reference Point 3:
End of straight segment of runway exit

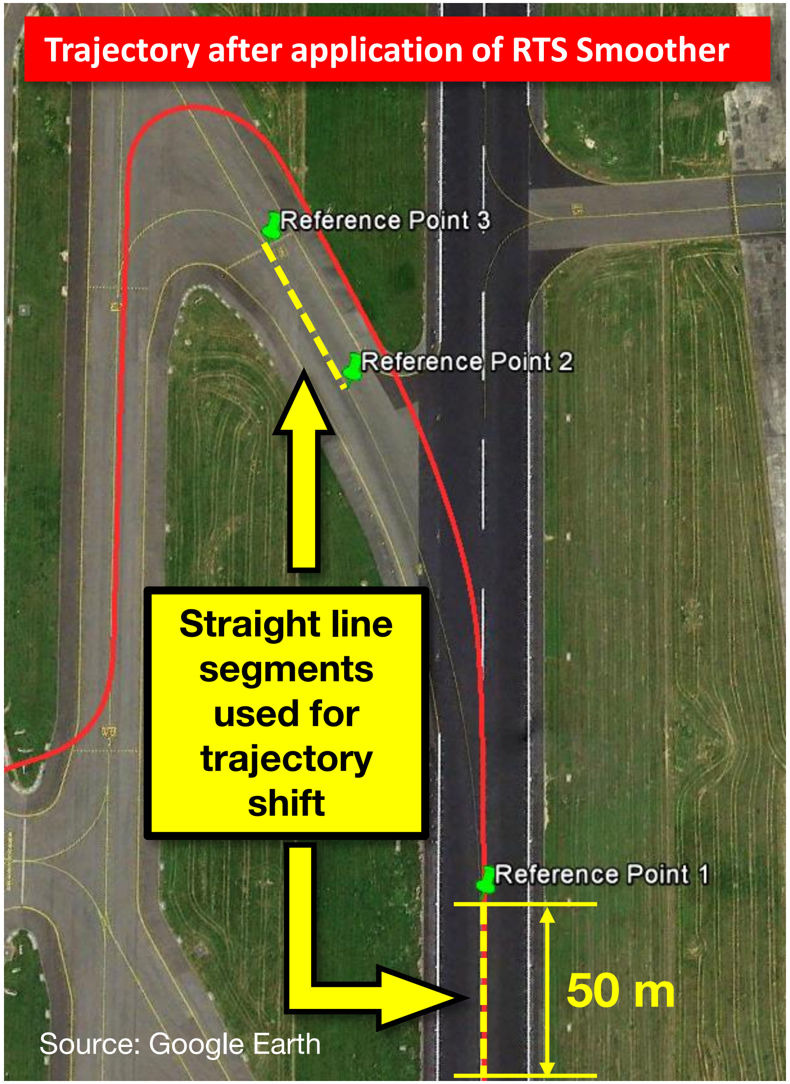
Reference Point 2:
Begin of straight segment of runway exit

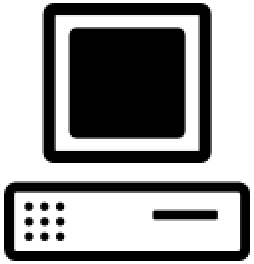
Remaining task:
Shift the trajectory in longitudinal direction

Shift correction is based on the assumption that pilots taxi on or close to the centerline during runway exit

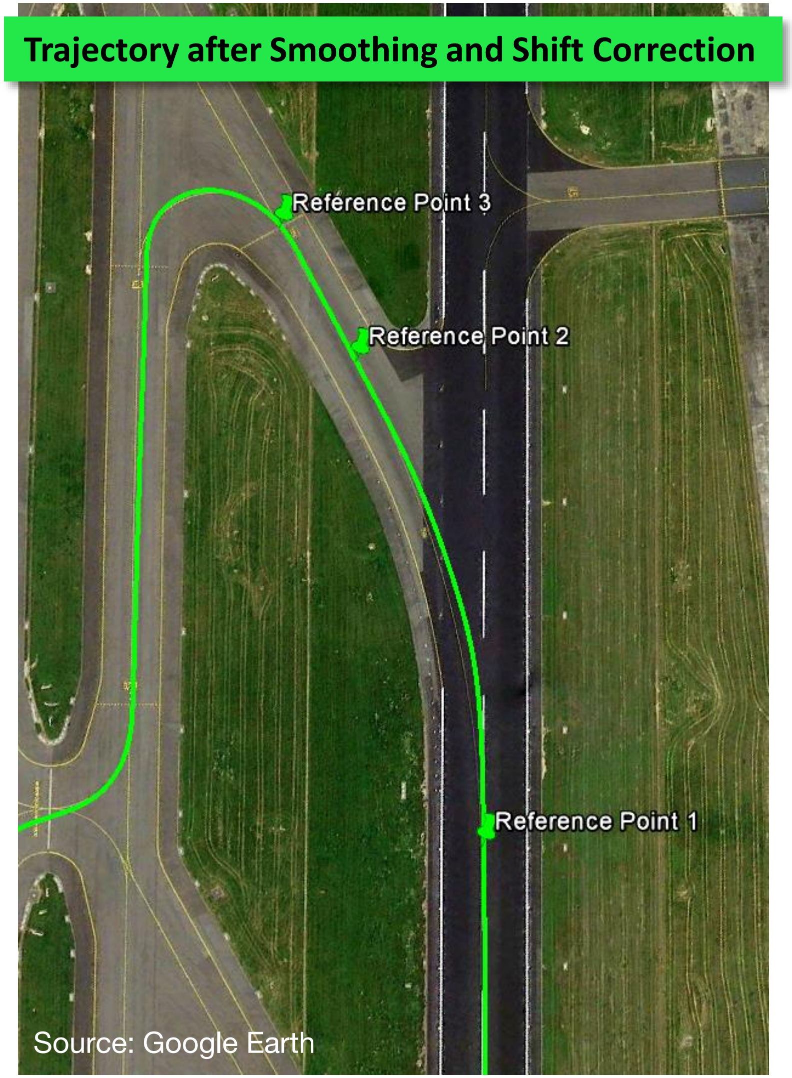
Reference Point 1:
On centerline at beginning of turn off

Longitudinal Shift Correction Based on Runway Exit

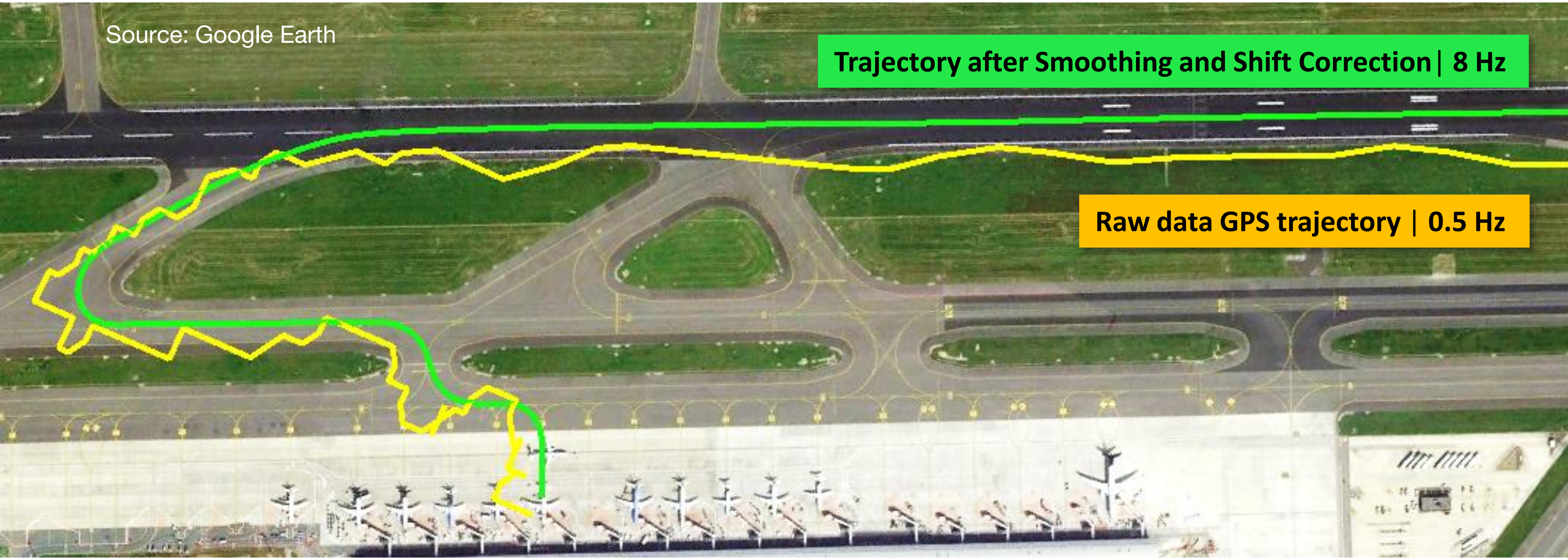




Automatic runway exit identification and shift correction



RTS Smoother Output



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

✓

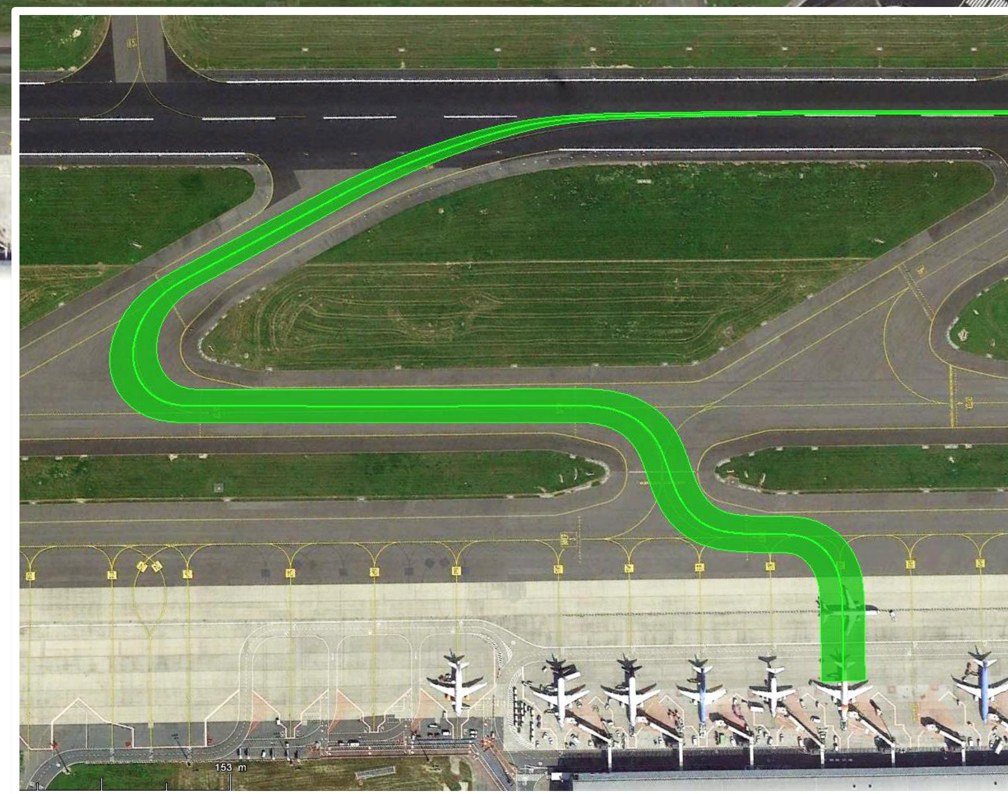
2.) Correct lateral offset

✓

3.) Correct longitudinal offset

✓

Final Result of Trajectory Reconstruction



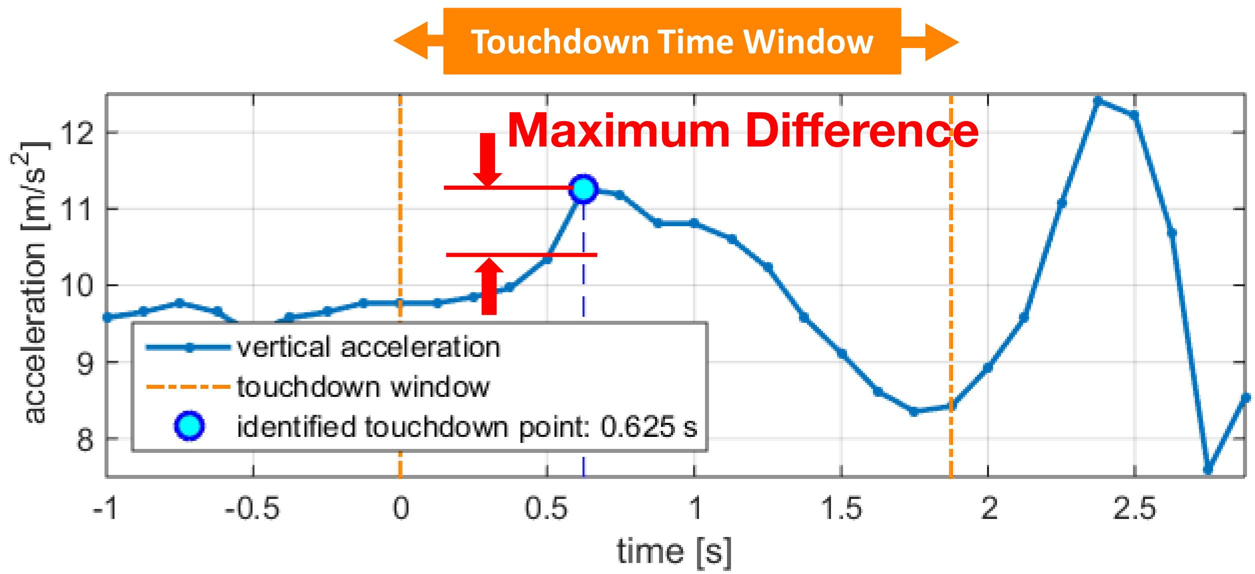
RTS-Smoother is able to estimate the aircraft trajectory together with the corresponding uncertainty for each time point

→ How accurate is the reconstructed trajectory?

Common Touchdown Point Detection Methods

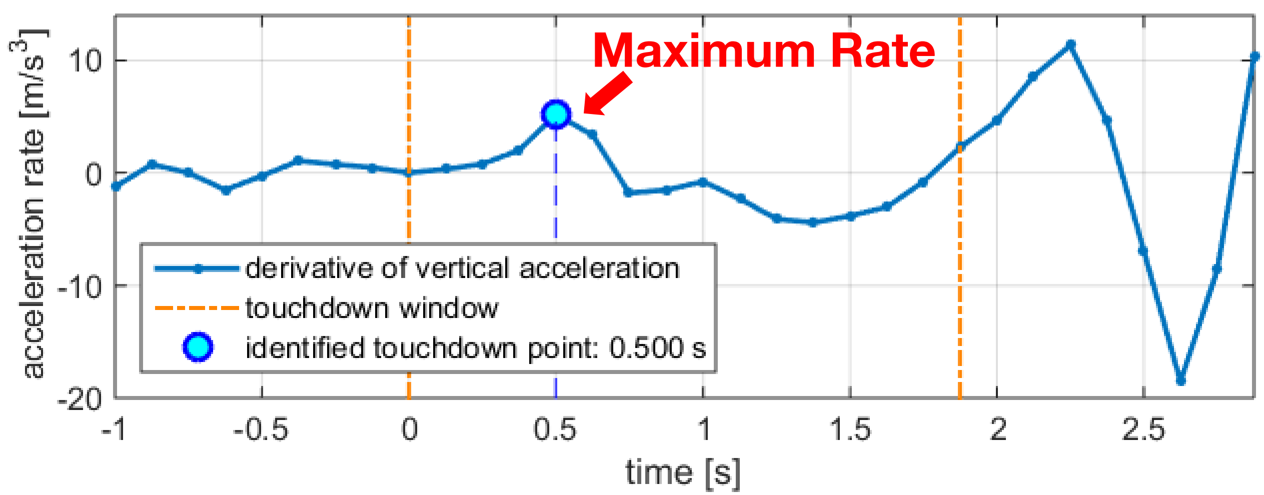
Method 1 - Maximum Difference Strategy

Seek highest difference in vertical acceleration



Method 2 - Maximum Rate Strategy

Seek maximum in derivative of vertical acceleration



Model Based Touchdown Point Detection

Angle of Attack

Angle of Attack Rate

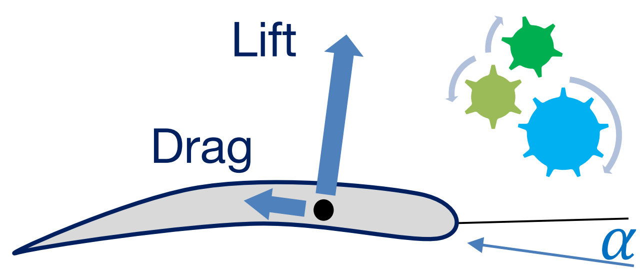
Pitch Rate

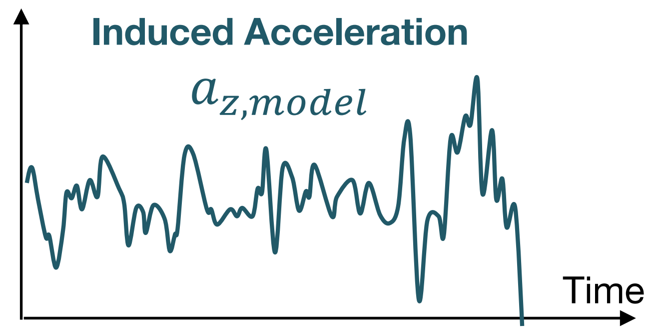
Elevator Deflection

Stabilizer Position

Spoiler Deflection

Aerodynamic Model for Vertical Acceleration $a_{z,model}$





Model DOES NOT include acceleration caused by ground reaction force

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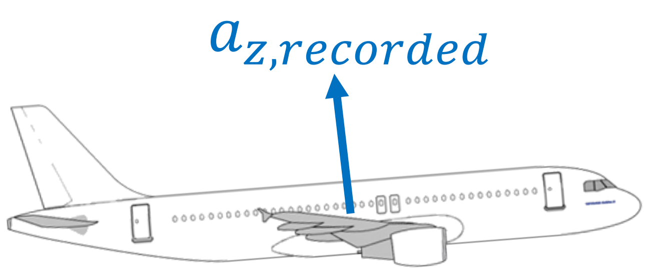
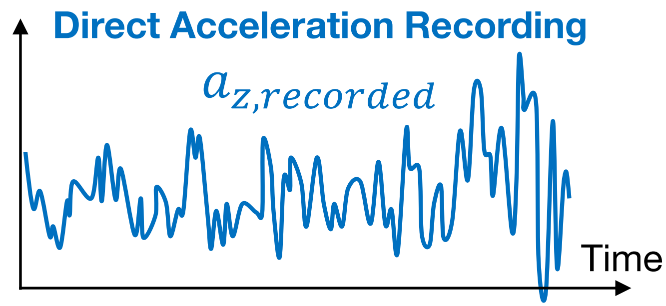
Vertical Acceleration

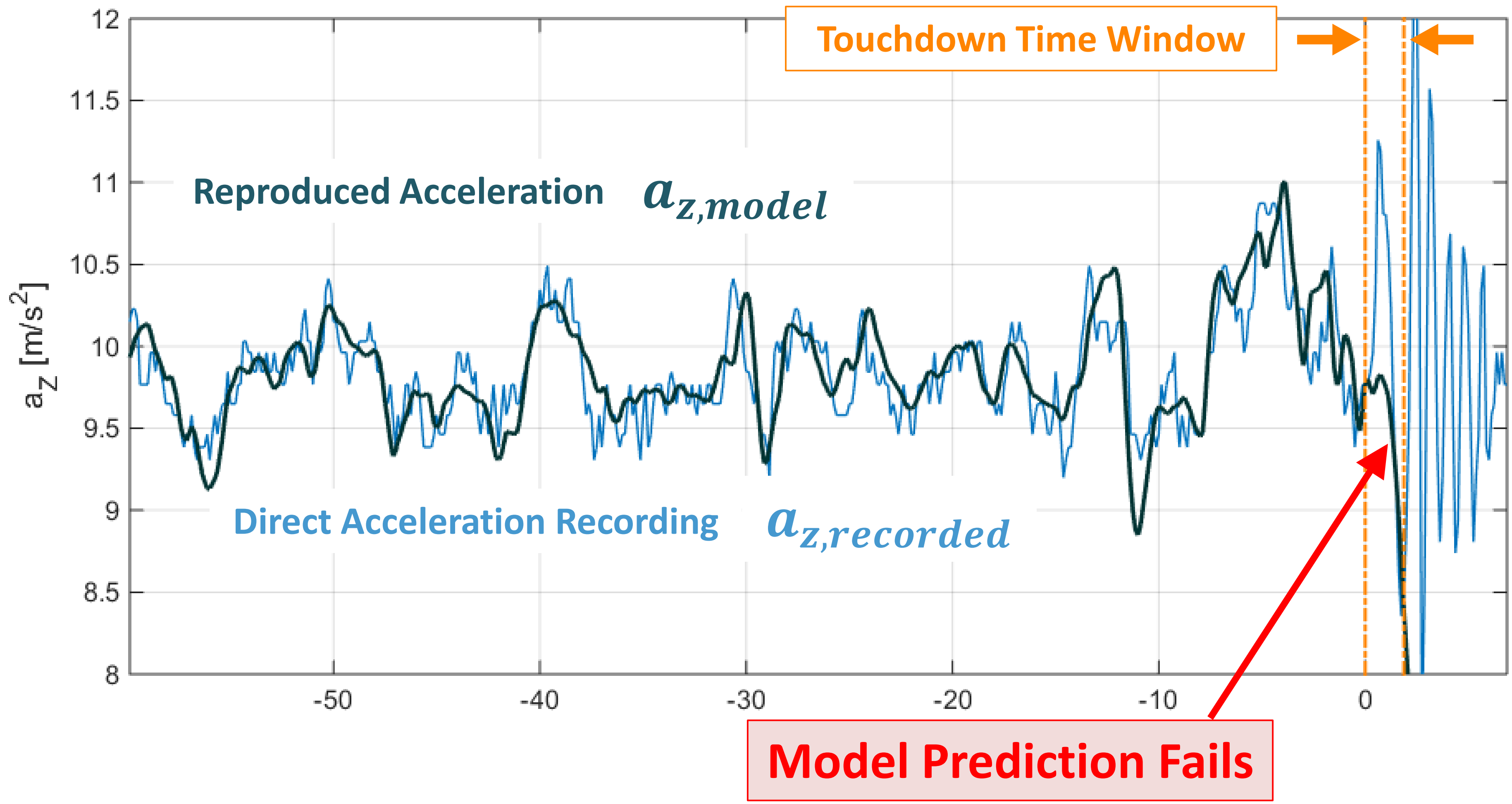
Direct Acceleration Recording $a_{z,recorded}$





Direct recording DOES include acceleration caused by ground reaction force

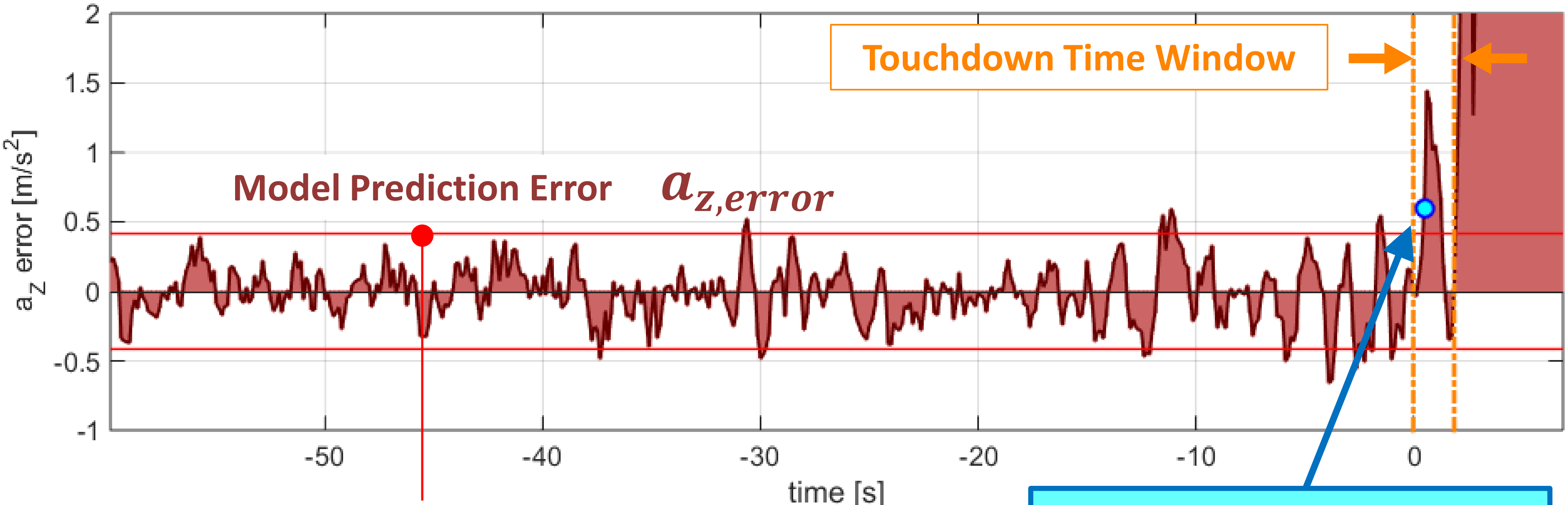
Model Based Touchdown Point Detection



Model Based Touchdown Point Detection

Metric to detect the model failure: Model Prediction Error

$$a_{z,error} = a_{z,recorded} - a_{z,model}$$



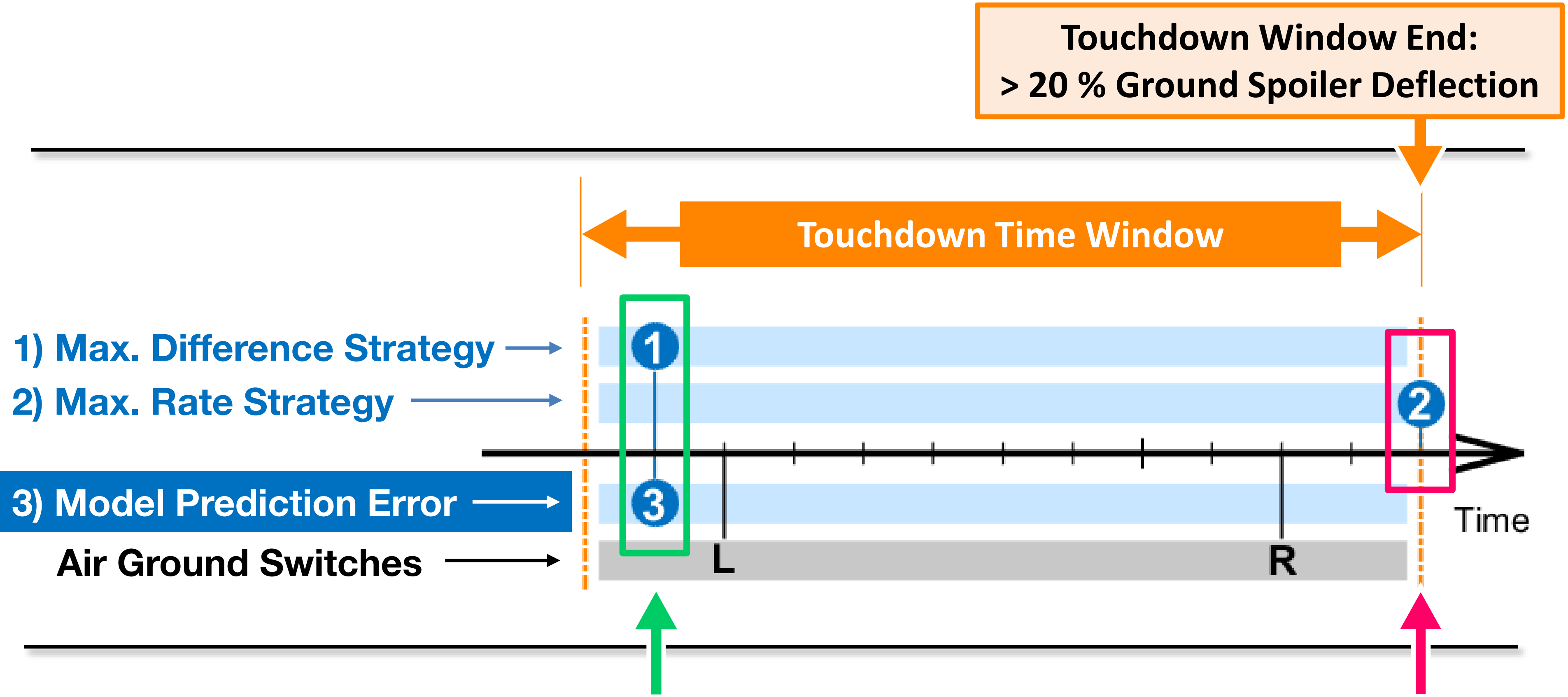
Boundary of 2 Standard Deviations

Identified Touchdown Point

Based on the model prediction errors before the touchdown time window

First time point with model prediction error at least 10 % above 2 sigma boundary

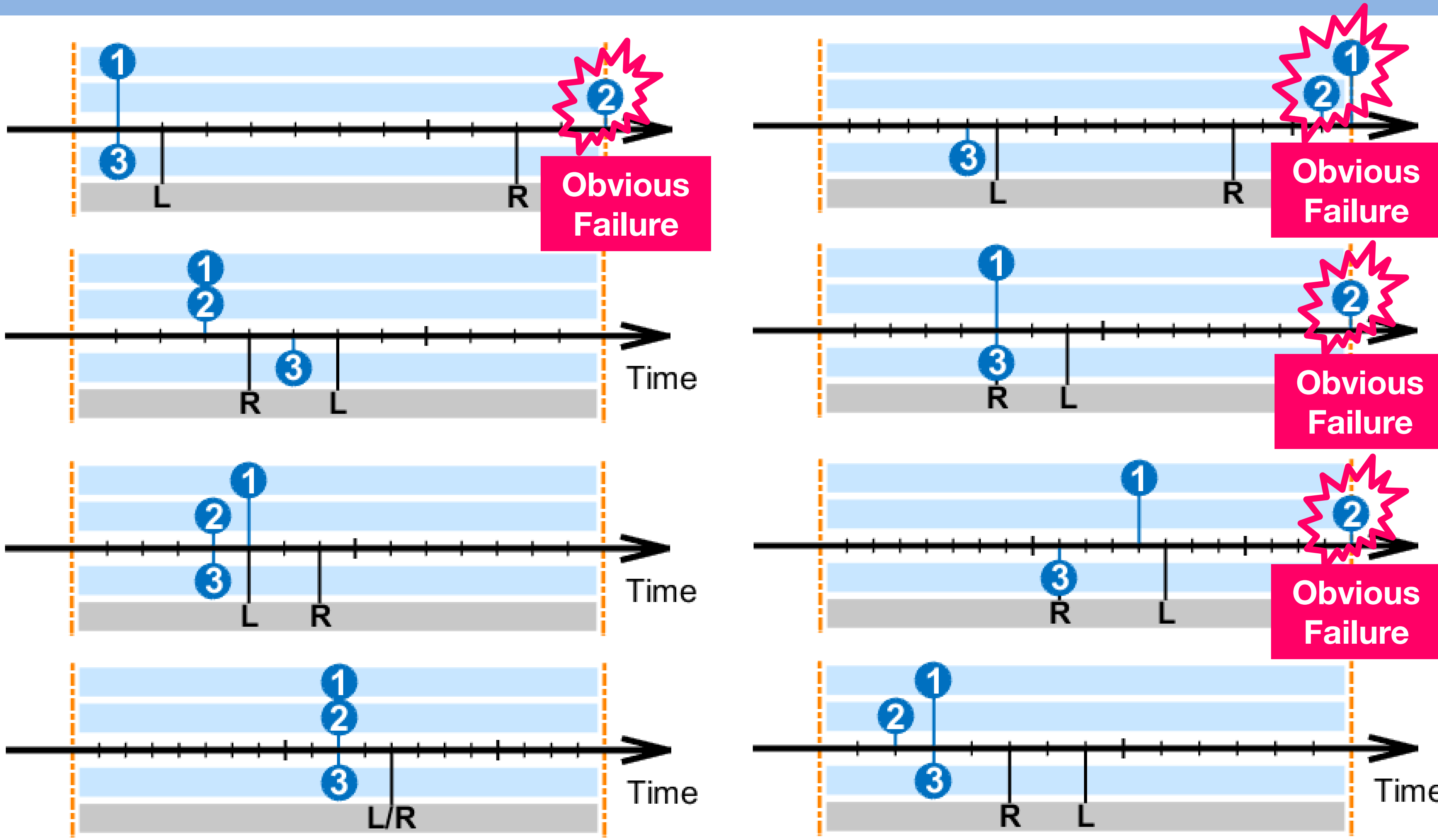
Results of the Touchdown Point Detection



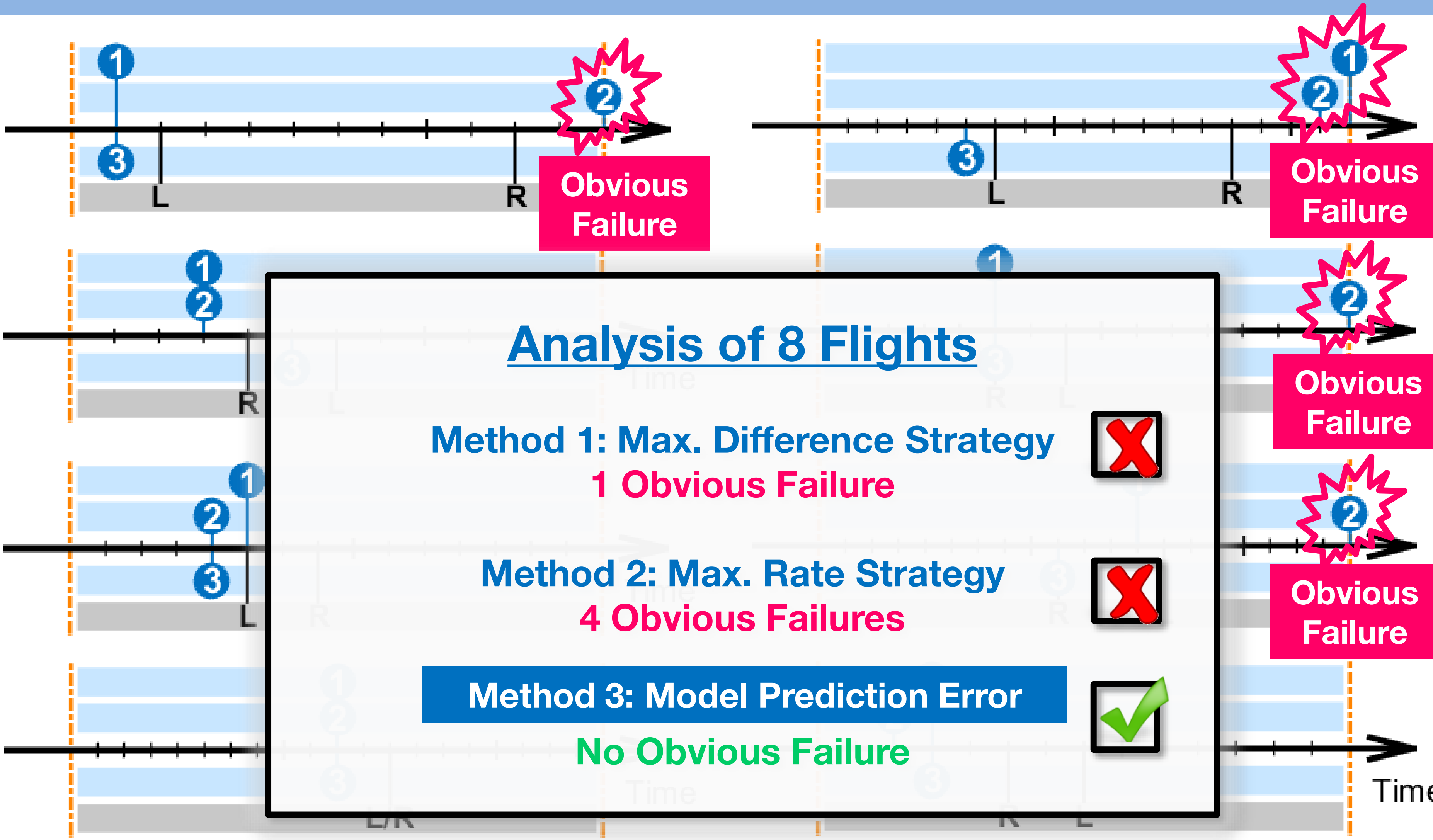
Consistent Result:
Close to first main gear air/ground switch triggering

Obvious Failure:
Detected touchdown after ground spoiler deployment

Results of the Touchdown Point Detection



Results of the Touchdown Point Detection



Analysis of 8 Flights

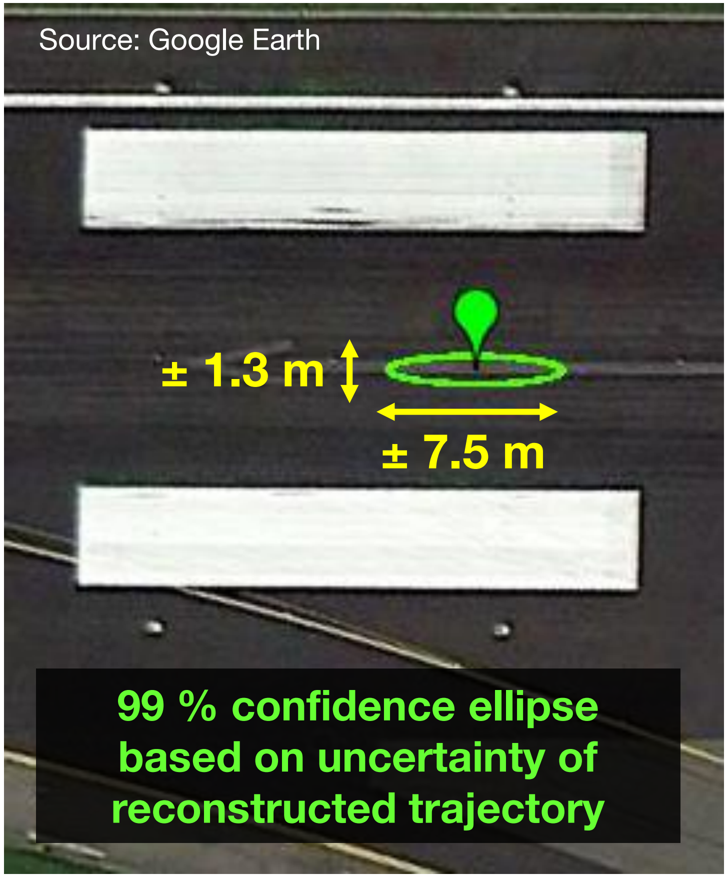
Method 1: Max. Difference Strategy
1 Obvious Failure

Method 2: Max. Rate Strategy
4 Obvious Failures

Method 3: Model Prediction Error
No Obvious Failure

Preliminary Accuracy Assessment

Touchdown Point Result:



Longitudinal Error (99 % confidence)

a) Uncertainty of trajectory	**± 7.5 m**
b) Taxiway shift correction error *	**± 5 to ± 10 m**
c) Touchdown time point detection **	**± 18 m**
Combined Error ($\sqrt{a^2 + b^2 + c^2}$)	**± 20 to ± 22 m**

Lateral Error (99 % confidence)

a) Uncertainty of trajectory	**± 1.3 m**
b) Taxiway shift correction error	**n.a.**
c) Touchdown time point detection	**± 0.5 m**
Combined Error ($\sqrt{a^2 + c^2}$)	**± 1.6 m**

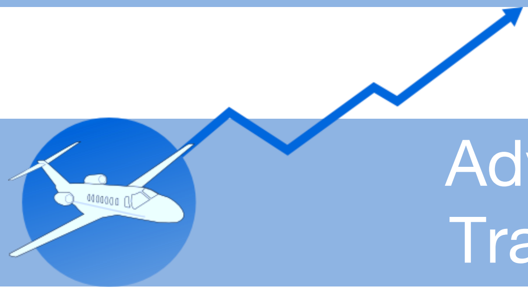
* Depending on taxiway angle / based on the assumption, that pilots taxi within ± 5 m of taxiway centerline 99 % of time

** Based on the assumption, that in 99 % of all cases the correct touchdown time point is identified within ± 2 samples

Future Plans

- Application of the algorithm to a variety of flights (especially in safety critical scenarios such as Florence airport)
- Verification and calibration of the algorithm (e.g. based on aircraft detection in video data or flight test data)
- Evaluate possibilities for integrating the algorithm into existing FDM software

Summary



Advantages of a Precise Landing Trajectory and Touchdown Point

Required First Step for Safety Investigations like Predictive Analysis

Enable Sophisticated Analysis of Touchdown Point Distributions

Reconstructed Trajectory and Touchdown

Accurate Landing Trajectory can be Used for Visualization and Debriefing

Besides Position, High Quality Reconstruction of Further States (e.g. Speed or Attitude) is Provided

Source: Google Earth, 2016 DigitalGlobe

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