ENRI International Workshop on ATM/CNS. Tokyo, Japan. (EIWAC 2009)

Trajectory Optimization for Safe, Clean and Quiet Flight

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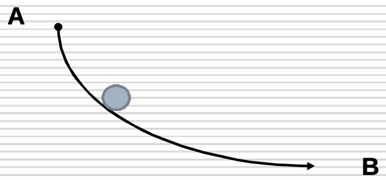
Trajectory Optimization

- ***Trajectory Optimization*** is formulated as an optimal control problem that finds the solution that maximizes or minimizes an objective function within constrained boundaries.

Calculus of variations

- Find the curve between two points that is covered in the least time by a body that starts at the first point with zero speed.



Brachistochrone curve

Johann Bernoulli

Numerical Optimization

- Pontryagin's Minimum Principle
- Bellman's Dynamic Programming
- Direct Numerical Optimization Method

$$\text{Minimize}: J = \int_{t_0}^{t_f} g(x,u)dt + h(t_f)$$

$$\text{Subject to}: dx/dt = f(x,u)$$

$$x(t_0) = x_0,\ x(t_f) = x_f$$

$$a(x,u) \le 0$$

Air Trafic Manegement

- NextGen
  - *Trajectory Management: Trajectory management includes any function that affects aircraft trajectory. These functions include* ***trajectory optimization*** *and negotiation with air traffic management, navigation algorithms, delegated aircraft separation applications, or trajectory constraints to avoid weather. The integration of these functions is* ***key to NextGen aircraft functionality.***

FAA, “Aircraft and Operator Requirements Solution Set Smart Sheet”

Flight Trajectory Optimization

- ***Safe*** Trajectory
  - Trajectory Generation for Emergency Landing
- ***Quiet*** Trajectory
  - Low Noise Trajectory Generation for Helicopter Landing Approach
- ***Clean*** Trajectory
  - Flight Management of Multiple Aircraft for CO_2 Reduction

Real-time Optimization in Emergency Landing Approach

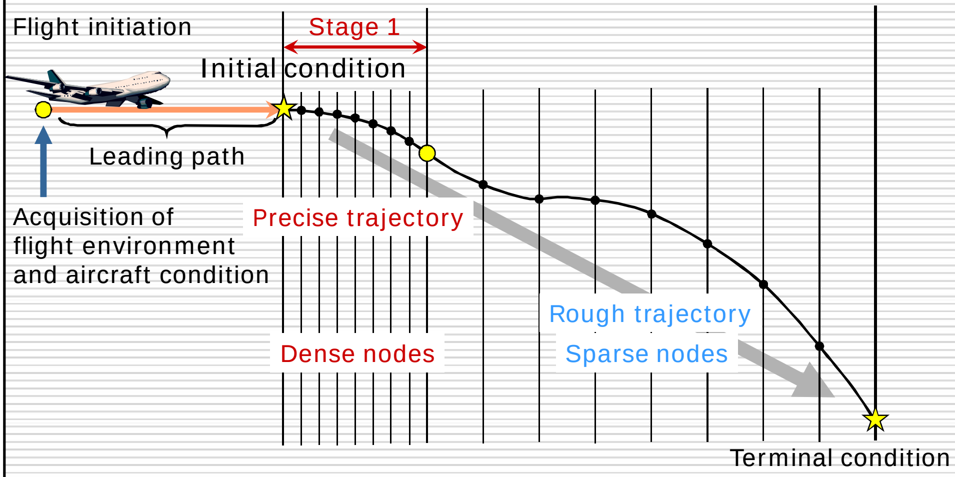
Ref: Y. Sakai, S. Suzuki., M. Miwa, T. Tsuchiya, and K. Maui, and H. Tomita, "Flight Test Evaluation of Non-Linear Dynamic Inversion Controller", 46th AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV/USA, 2008.1.8.

Purpose

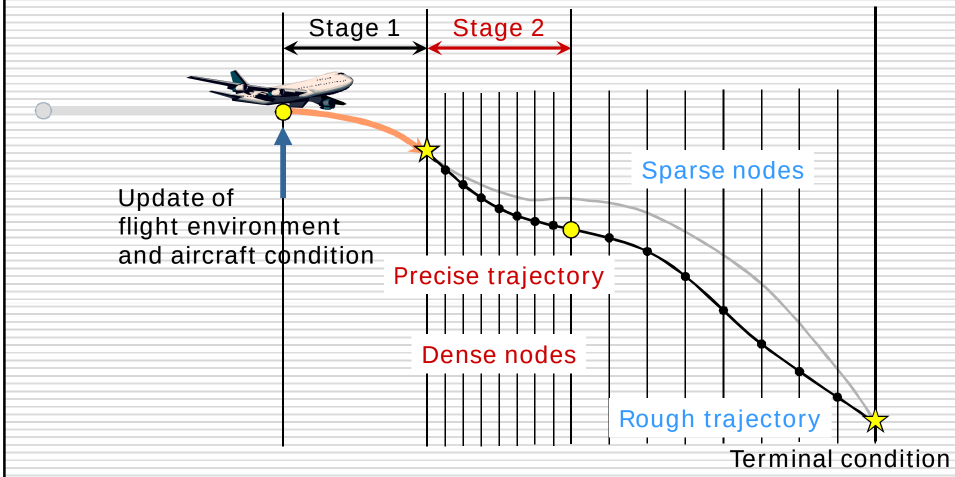
- In an emergency, as part of a fault-tolerant flight control system, generate an optimal flight trajectory to the nearest airport in real time.

Funded by the Ministry of Economy, Trade, and Industry (METI) and organized by the Society of Japanese Aerospace Companies.
Joint Research Between the Univ of Tokyo and JAXA

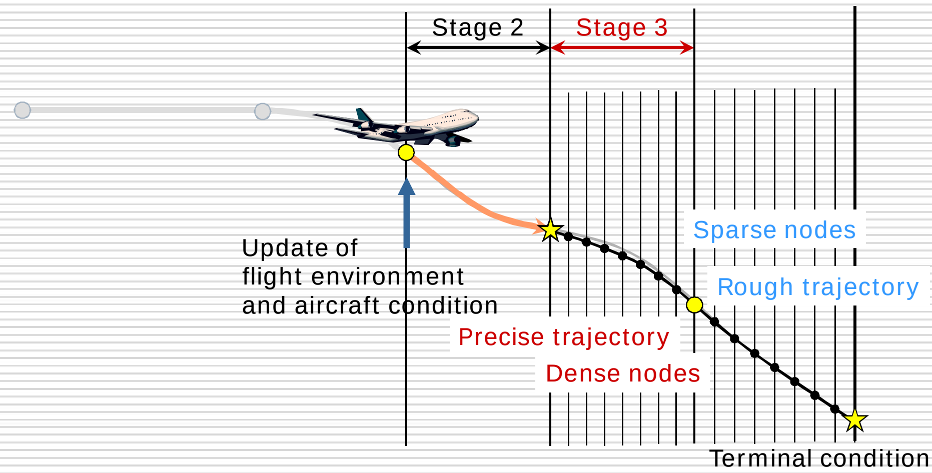
Real-Time Trajectory Optimization method



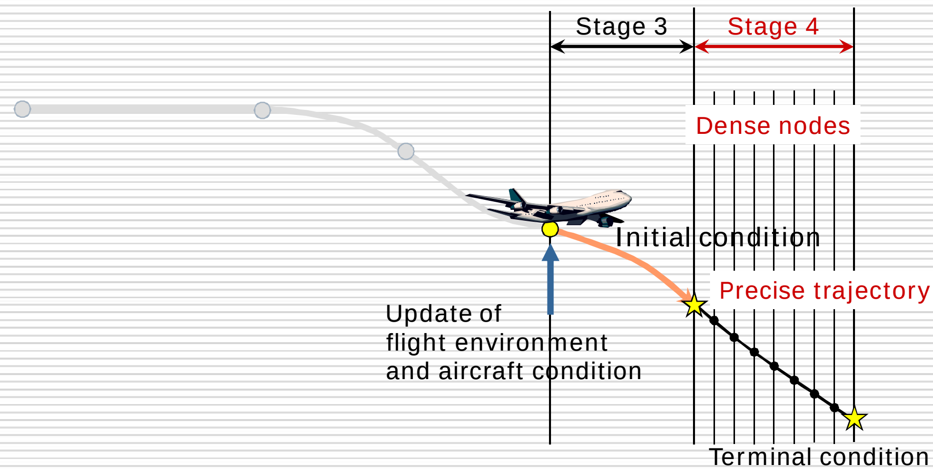
Real-Time Trajectory Optimization method



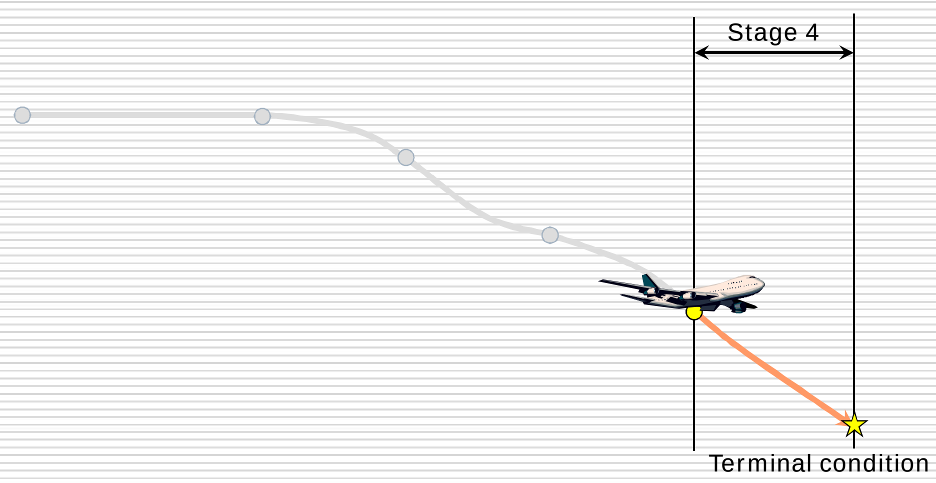
Real-Time Trajectory Optimization method



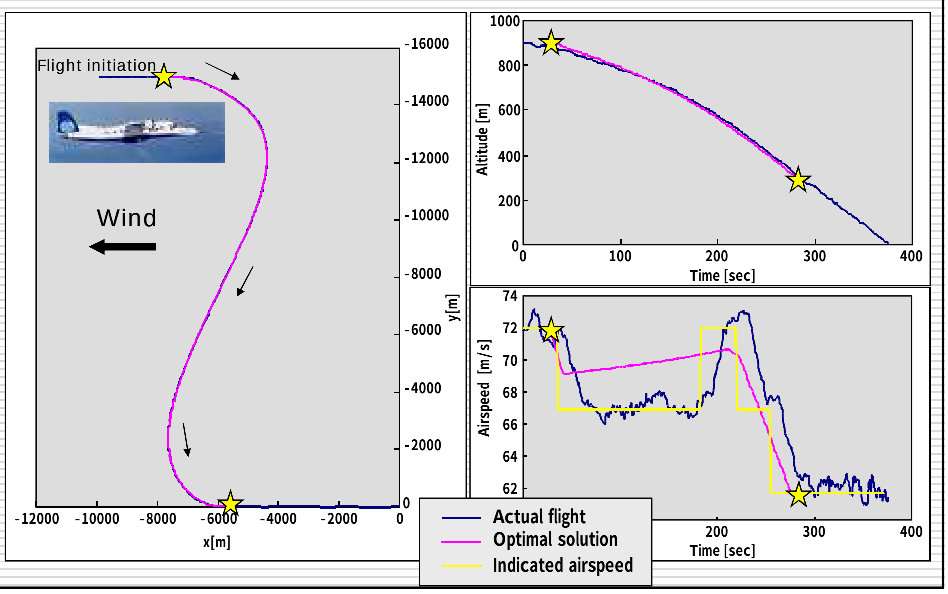
Real-Time Trajectory Optimization method



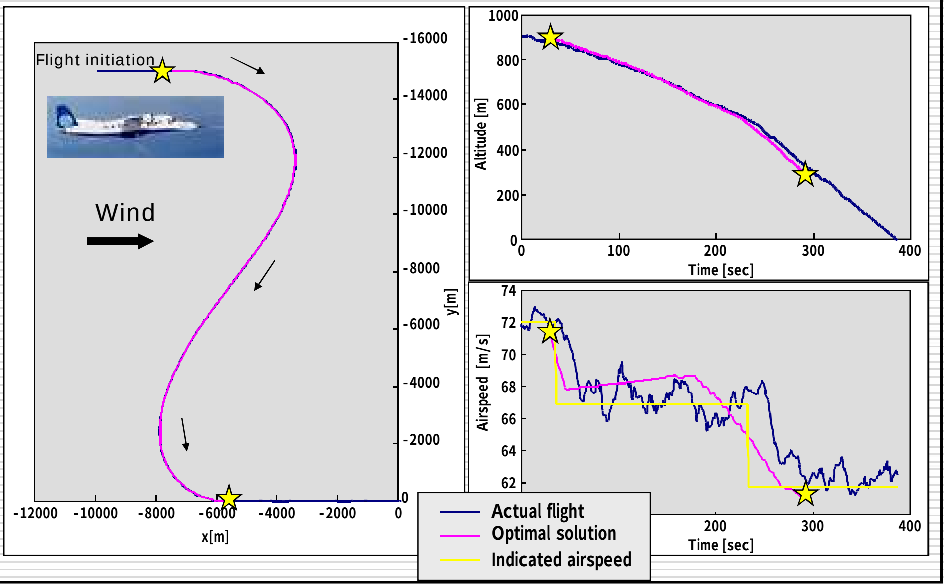
Real-Time Trajectory Optimization method



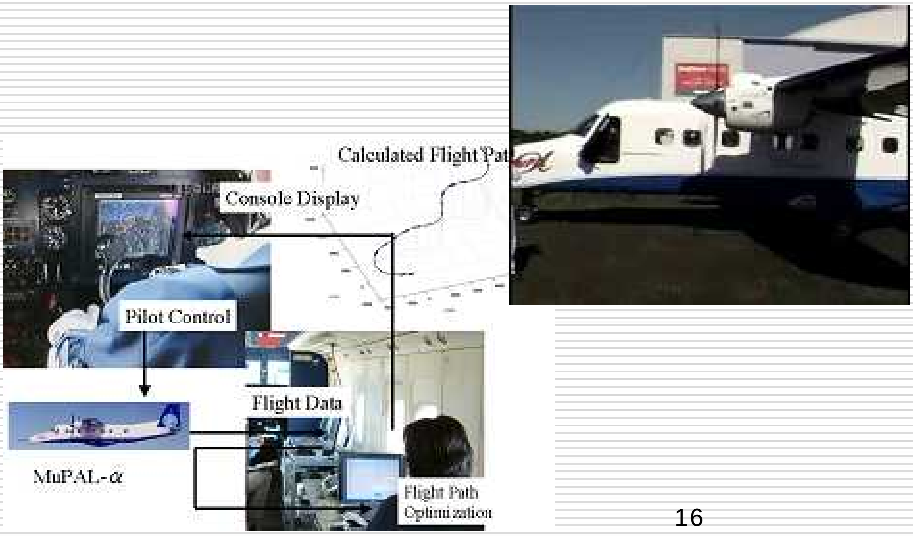
Flight-test results



Flight-test results



Flight Testing



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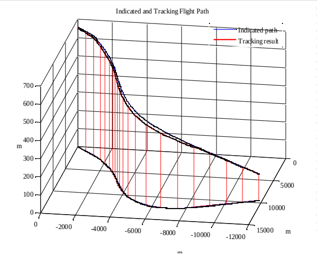
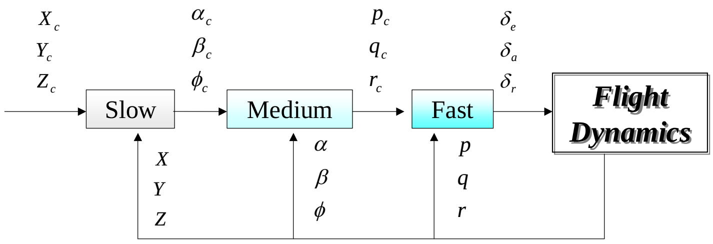
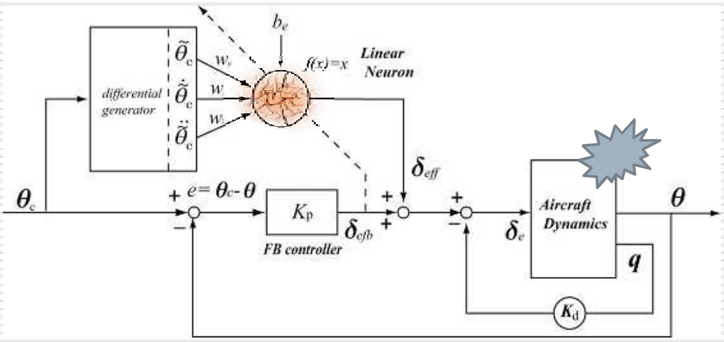
Auto Pilot + Auto Throttle using 4D Navigation





Fault Tolerant Flight Control

- Neural Network can learn the change of dynamic characteristic due to failure in flight.



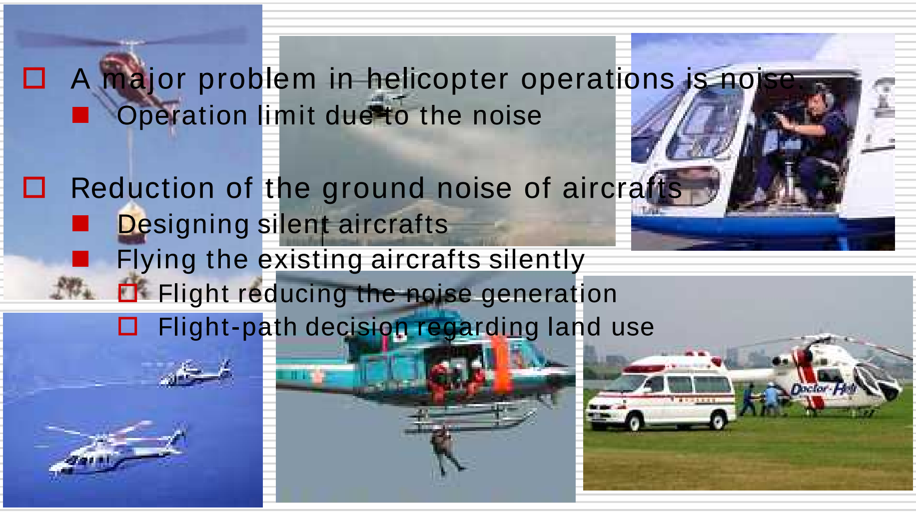
Flight Demonstration

Small Electric Power UAV
・Takeoff weight 2 kg
・Automatic Flight Capability
Developed by U of Tokyo and Mitsubishi Electric Co.

Ground Noise Reduction in Helicopter Landing Approach

Ref: T. Tsuchiya, H. Ishii, J. Uchida, H. Ikaida, H. Gommi, N. Matayoshi, and Y. Okuno, "Flight Trajectory Optimization to Minimize Ground Noise in Helicopter Landing Approach", J. Guidance, Control and Navigation (to appear)

Introduction



- A major problem in helicopter operations is noise
  - Operation limit due to the noise
- Reduction of the ground noise of aircrafts
  - Designing silent aircrafts
  - Flying the existing aircrafts silently
    - Flight reducing the noise generation
    - Flight-path decision regarding land use

Purpose

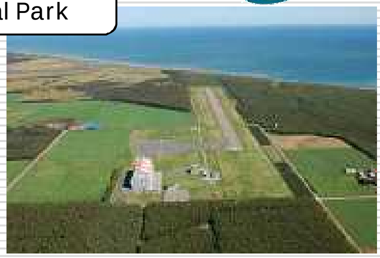
- Optimizing helicopter flight trajectories to reduce ground noise in the landing approach

Trajectory optimization (University of Tokyo)

Flight demonstration (JAXA)

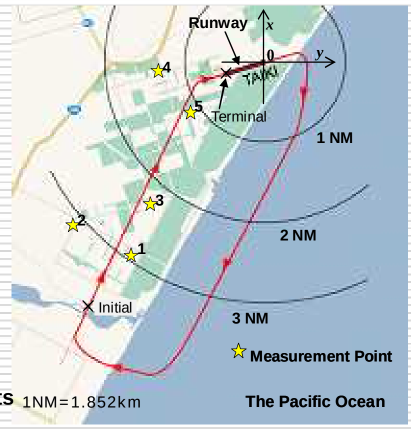
Collaborative Research

Flight test field



Problem definition

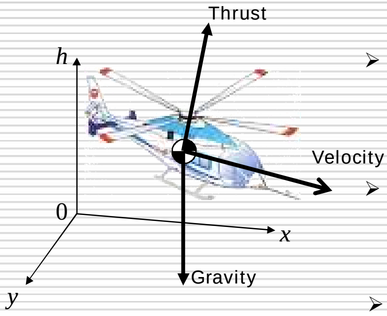
☆ noise measurement points



Find optimal trajectories minimizing the noise levels measured at the five measurement points

The optimal trajectories are computed before flight, and a pilot tracks it manually.

Helicopter dynamics model



3DOF (point-mass model)

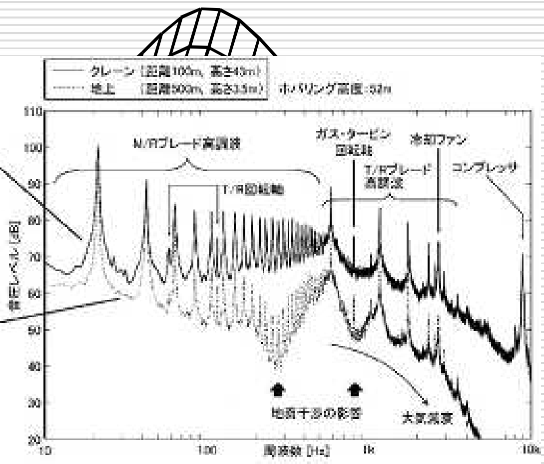
- Horizontal-velocity limit
  $50 \le$ horizontal velocity ≤ 100 [kt]
- Climb rate limit
  climb rate ≥ -800 [fpm] (Altitude $h \ge 480$ [ft])
  $\ge -\frac{5}{3}h$ [fpm] (Altitude $h < 480$ [ft])
- Acceleration limit
  $|$horizontal acceleration$| \le 1.5$ [kt/sec]
  $|$vertical acceleration$| \le 100$ [fpm/sec]
- Roll angle limit
  $|$roll angle$| \le 15$ [deg]

Define the constraint conditions from pilot comments

JAXA Simulator

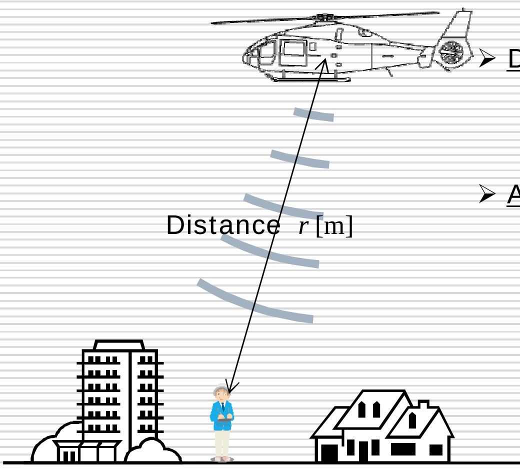
Noise source model

Microphone array system



The level at a distance of 100 m from the helicopter

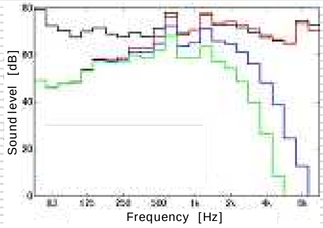
Attenuation model



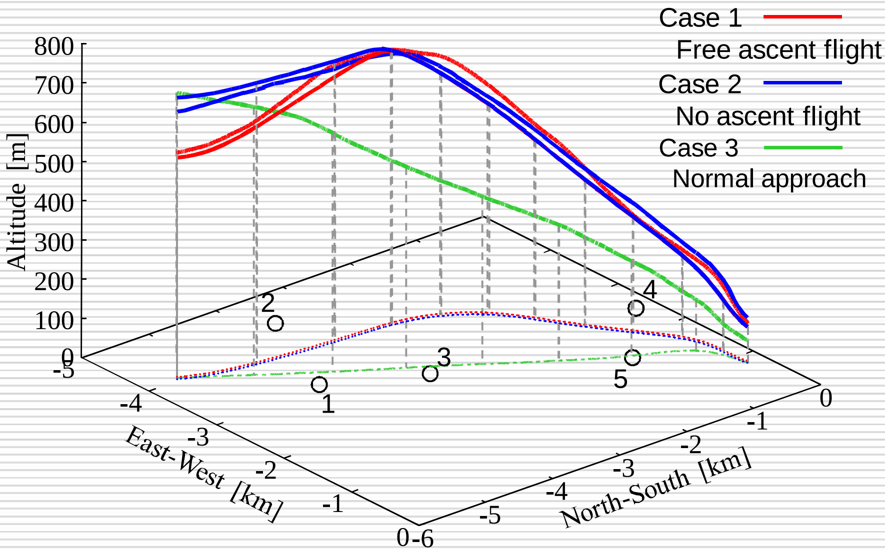
- **Distance absorption**

$$att_{dist}(r) = 20\log\frac{r[\mathrm{m}]}{100[\mathrm{m}]}[\mathrm{dB}]$$

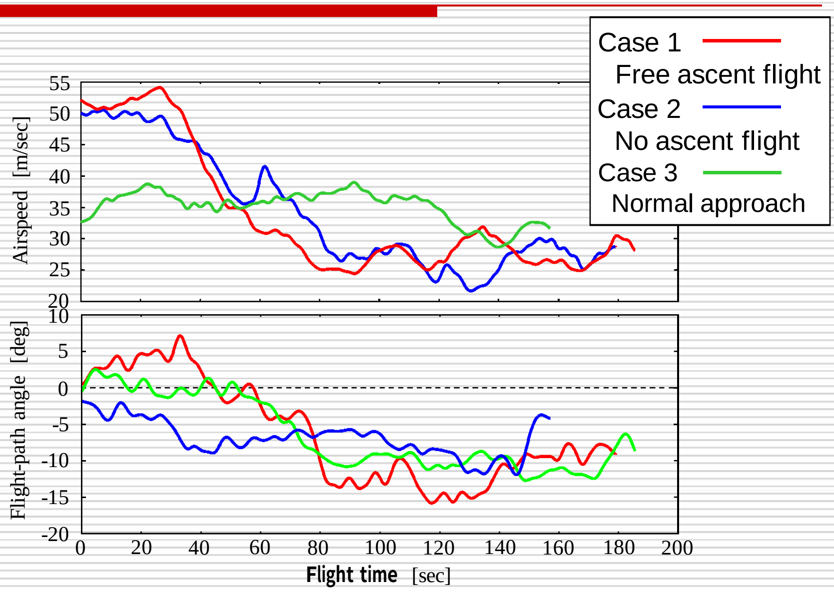
- **Atmospheric absorption**



Flight-test results



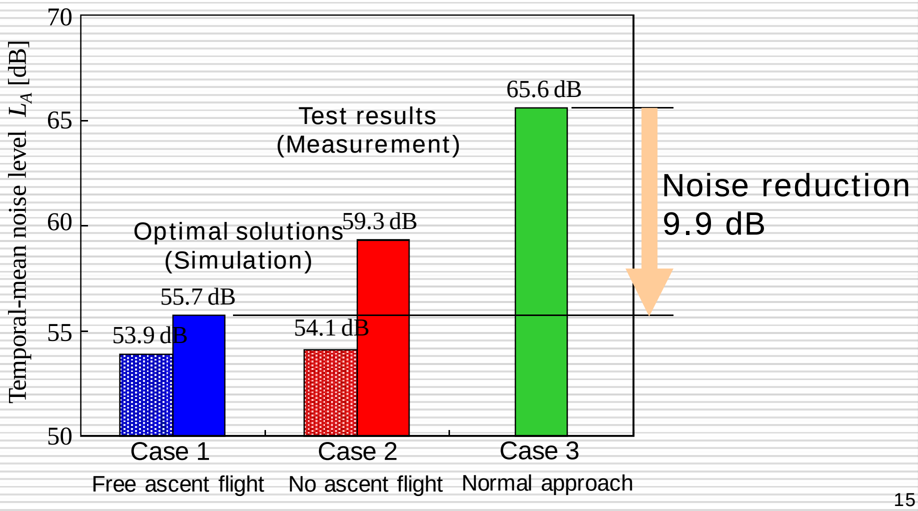
Flight-test results



Flight scene

Flight scene

Noise-reduction result



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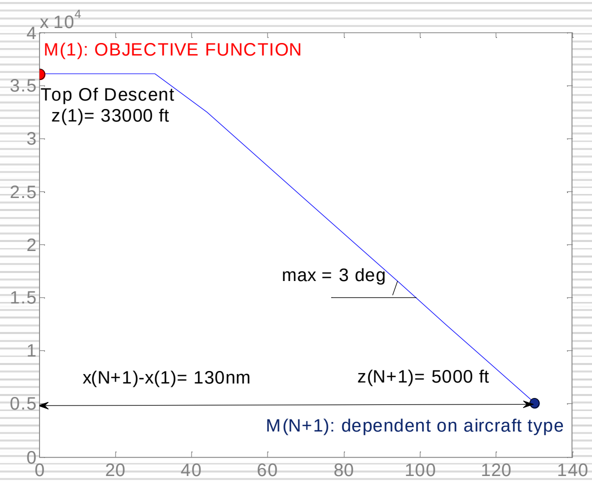
Multiple Aircraft Descent Trajectory Optimization with Air Traffic Constraints for Minimal Fuel Consumption

Adriana Hristova Andreeva,
Shinji Suzuki (Univ of Tokyo)
Eri Itoh (ENRI)

Ref: A. Andreeva, S. Suzuki, and E. Ito, "Multiple Aircraft Descent Trajectory Optimization with Air Traffic Constraints for Minimal Fuel Consumption", International Conference on Mathematical Problems in Engineering, Aerospace and sciences, ICNPAA-2008, Genoa, 2008.

Optimal Decent Trajectory of Single Aircraft



- Waypoint *i* position: *(x(i), y(i), z(i))*
- Sequential Qudratic Programming (SQP)
- MATLAB®

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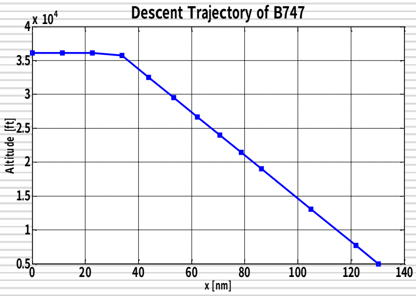
Optimal Decent Trajectory of Single Aircraft

- Higher for longer

$$\rho = \rho_0 \left[1 - \frac{6.5 * h}{1000 * T_0} \right]^{-\frac{g}{K_T R} - 1}$$



$$M_{fuel\_B747} = M_{initial} - M_{final} = 12065 \quad lb$$

$$t_{total\_B747} = 1530.2 \quad s$$

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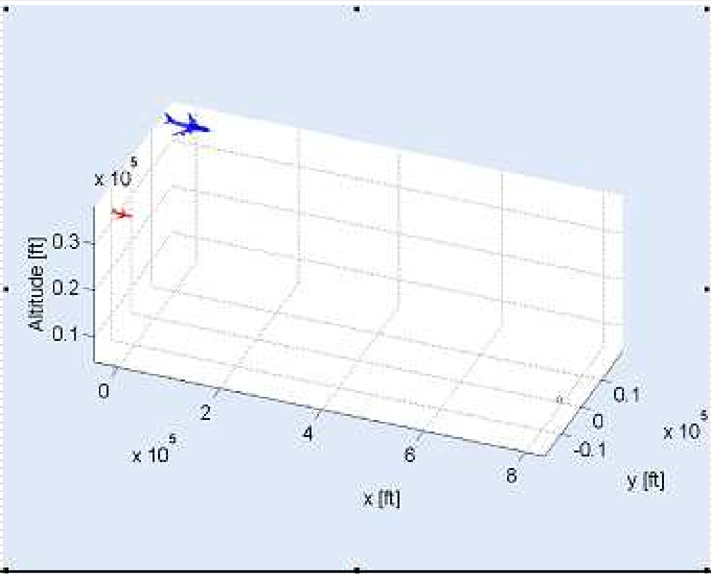
Two Aircraft Case



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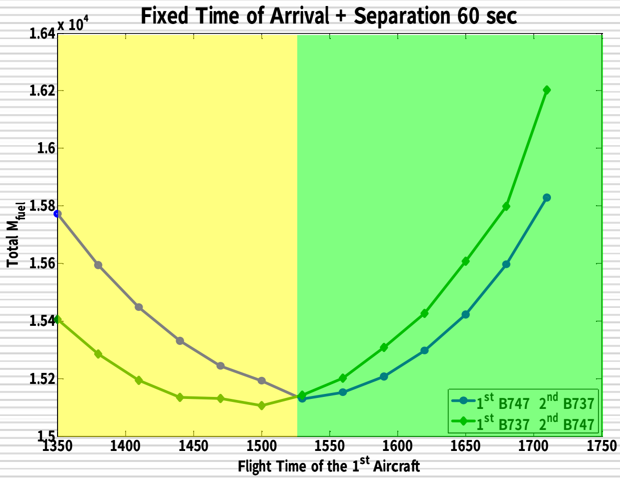
Two Aircraft Case



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Summary

- A numerical method for trajectory optimization problem
- Application to real flights
  - Ground noise reduction in helicopter landing approach
  - Trajectory generation in emergency landing approach
- Air traffic management