KYUSHU UNIVERSITY 2011
100th Anniversary

[EN-041] A Study on Benefits Gained by Flight Trajectory Optimization for Modern Jet Passenger Aircraft

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- Outline -

- **Premise of Study**
- **Research Motivation**
- **Mathematical Formulation**
- **Dynamic Programming Method**
- **Utilized Models** – Meteorological Model, Aircraft Performance Model
- **Reference Data**
- **Flight Trajectory Optimization** – Examples & Effect of Wind Shear
- **Conclusions**

- Premise of Study -

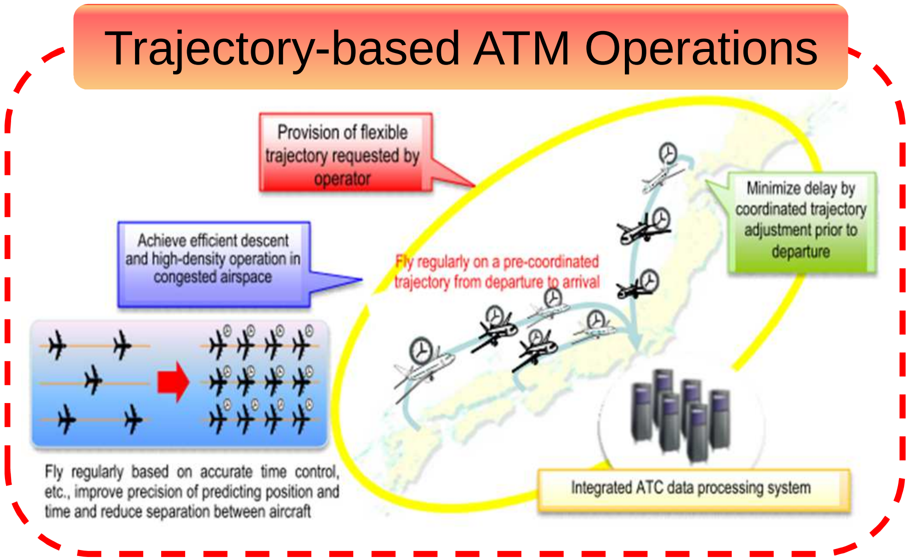
Trajectory Based Operations Concept

NextGen Program | SESAR Program | CARATS Program

Reduce operational cost / environmental impact

Efficient and flexible airspace with user priority

Increased Safety



Courtesy: CARATS Long Term Vision for the Future Air Traffic Systems

- Research Motivation -

Towards an Efficient Operational System... **"Free Flight"**

- ✓ Safe and efficient **User Priority** flight path and speed selection in real time **according to weather conditions**
- ✓ System's flexibility to manage capacity increase
- ✓ Economic benefits such as **Fuel Consumption Reduction** with Departure→Arrival direct approach

Reviewing the benefits obtained by **flight trajectory optimization** by **minimizing fuel consumption considering the presence of winds** in a **Free Flight based** futuristic Air Transportation System

- Requirements for Analysis -

Optimization Tool

Dynamic Programming Method

Meteorological Data

Numerical Weather Prediction Model Data

Aircraft Performance Model

Base of Aircraft Data (BADA) Model

Reference Data

Recorded Flight Data on GPS Logger

4D- Flight Trajectory Optimization

- Mathematical Formulation -

3D- Translational Motion : $P_1(\phi_1, \theta_1, H_1, V_{\mathrm{TAS}_1}) \rightarrow P_2(\phi_2, \theta_2, H_2, V_{\mathrm{TAS}_2})$

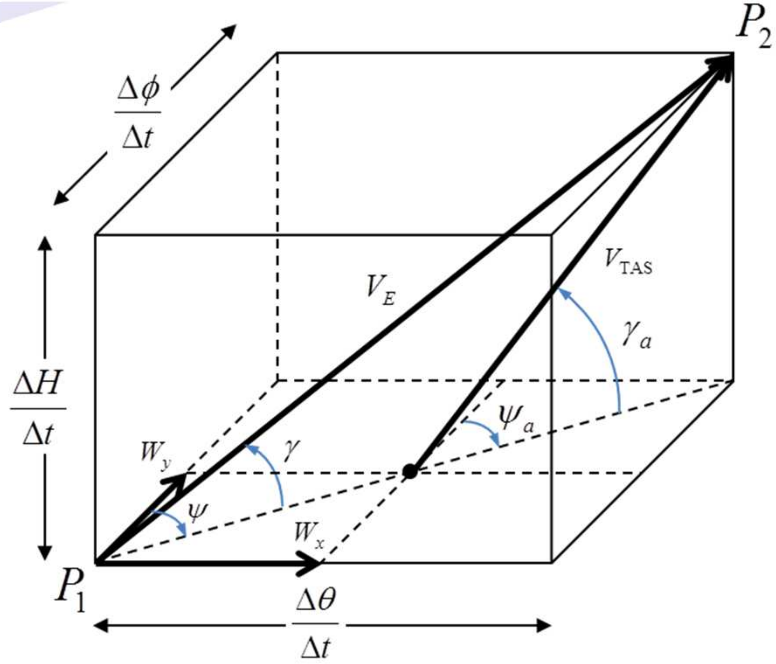
$$\dot{\phi} = \frac{V_{\mathrm{TAS}} \cos\gamma_a \cos\psi_a + W_v(\phi, \theta, H)}{R + H}$$

$$\dot{\theta} = \frac{V_{\mathrm{TAS}} \cos\gamma_a \sin\psi_a + W_u(\phi, \theta, H)}{(R + H)\cos\phi}$$

$$\dot{H} = V_{\mathrm{TAS}} \sin\gamma_a$$

$$m\dot{V}_E \cos(\gamma_a - \gamma)\dot{V}_{\mathrm{TAS}} = T - D - mg\sin\gamma_a$$

ϕ : Latitude
θ : Longitude
H : Altitude
V_{TAS} : True airspeed
T : Engine thrust
D : Aerodynamic drag
V_E : Aircraft's speed on Earth Frame
R : Earth radius
W_u : Zonal wind component
W_v : Meridional wind component
γ_a : Flight path angle
ψ_a : Heading angle

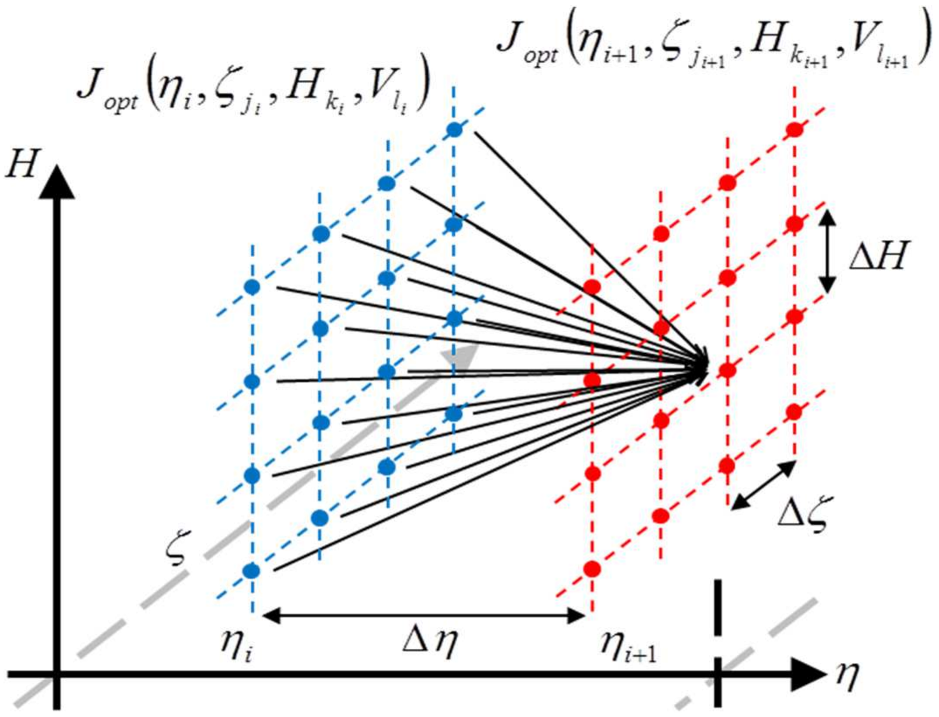


Definition of point mass equations

State Variables	Control Variables
ϕ , θ , H , V_{TAS}	γ_a , ψ_a , T

- Dynamic Programming Method -

Performance Index : $J_{\mathrm{opt}} = \int_{t_0}^{t_f} FF\, dt$ (FF : fuel flow)



Performance index calculations

Independent Variable

η

State Variables

H, V_{CAS}, ζ

η : Downrange angle

ζ : Cross range angle

H : Altitude

V_{CAS} : Calibrated airspeed

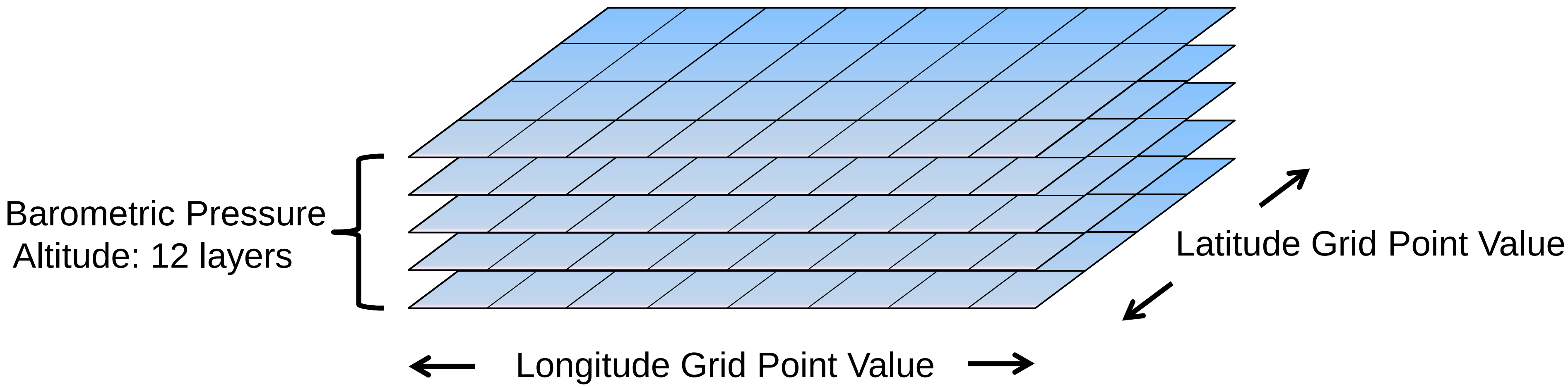
Reference: [EN-040] Harada, A., Miyamoto, Y. and Wickramasinghe, N.K.,
"Flight Trajectory Optimization Tool with Dynamic Programming Developed for Future Air Transportation System"

- Meteorological Model -

- Weather data from Japan Meteorological Agency (JMA)

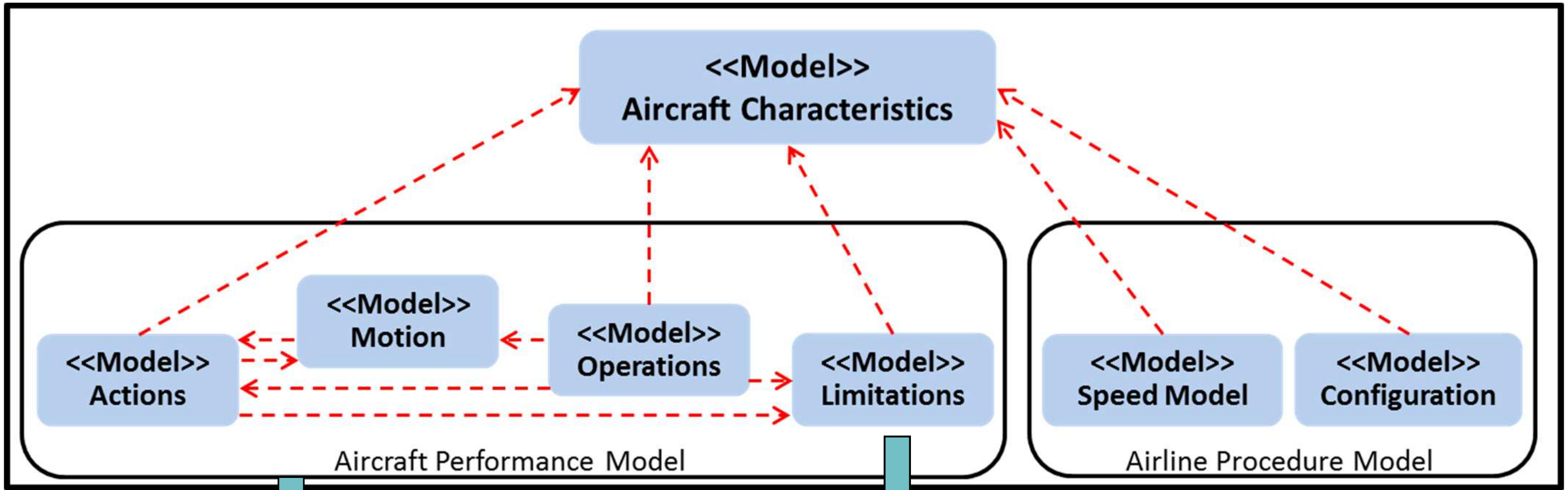
Characteristics of GSM Japan Region Model

Data Format	GRIB2 Grid Point Value (GPV) Data
Initial Time Value	00, 06, 12, 18 (UTC)
Region	Longitude: $120^\circ \sim 150^\circ [\mathrm{deg}]$ Latitude: $20^\circ \sim 50^\circ [\mathrm{deg}]$
Resolution	Longitude Direction: $0.25^\circ [\mathrm{deg}]$ Latitude Direction: $0.20^\circ [\mathrm{deg}]$
Pressure Altitude	$1000,925,850,700,600,500,400,300,250,200,150,100 [\mathrm{hPa}]$
Physical Elements	Geopotential Altitude, Zonal wind, Meridional wind, Temperature, vertical flow



- Aircraft Performance Model -

- BADA (Base of Aircraft Data) by EUROCONTROL



Courtesy: EUROCONTROL

Utilized models

- ✓ Aerodynamic Model
- ✓ Thrust Model
- ✓ Fuel Flow Model

Constraint Conditions

$$VMO \geq V_{\mathrm{CAS}} \geq 1.3 \times V_{\mathrm{STALL}} \qquad T_{\max} \geq T$$

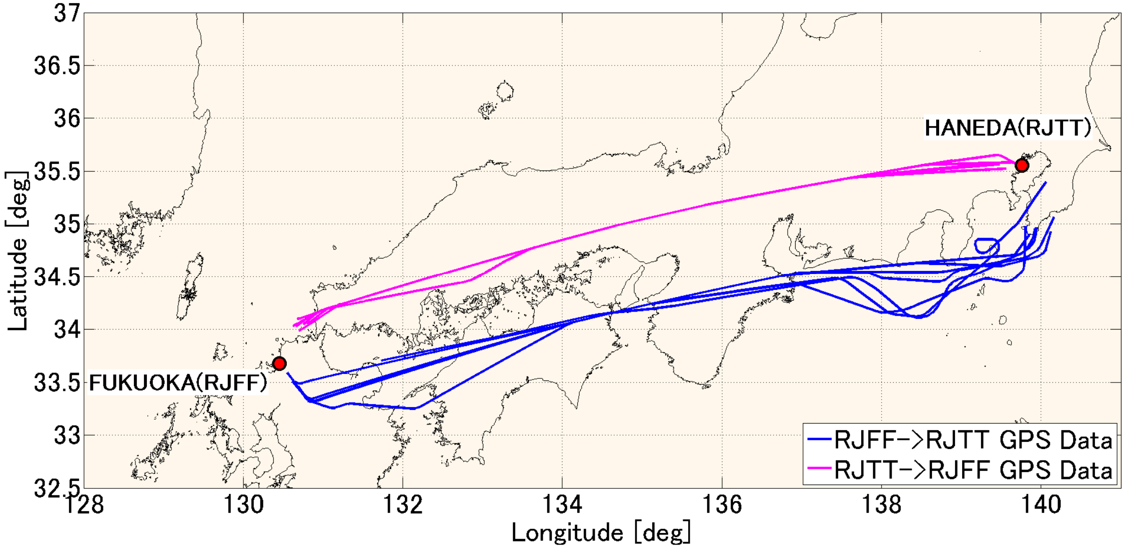
$$MMO \geq Mach\ \ Number \qquad FF = \max\left(FF_{\mathrm{nom}}, FF_{\mathrm{min}}\right)$$

- Reference Data -

Data recording

Accuracy check

Lateral measurement error:
3 ~ 25 [m] at ground level
(Courtesy: Google Maps)



Recorded total flight routes

Measured Data
Time of Measurement
Longitude [deg, mts, sec]
Latitude [deg, mts, sec]
Ground Velocity [km/h]
Geometrical Altitude [m]

Reference: [EN-039] Totoki, H. and Wickramasinghe, N.K.,
"A Study on Flight Trajectory Estimation by Using GPS Data Measured in Airliner Cabin"

- Problem Setting -

Calculation Conditions

<table>
<tr><td>Reference Route</td><td colspan="3">Haneda : 35.5483^{0}N 139.9078^{0}E
Fukuoka : 33.8903^{0}N 130.3317^{0}E</td></tr>
<tr><td>Downrange</td><td colspan="3">30 Grid points</td></tr>
<tr><td rowspan="2">Altitude</td><td>Minimum</td><td>3000[m]</td><td rowspan="2">100
Grid Points</td></tr>
<tr><td>Maximum</td><td>13000[m]</td></tr>
<tr><td rowspan="2">Calibrated Airspeed</td><td>Minimum</td><td>100[m/s]</td><td rowspan="2">60
Grid Points</td></tr>
<tr><td>Maximum</td><td>160[m/s]</td></tr>
<tr><td>Cross range</td><td colspan="3">2.5[deg] on each side of Great Circle Route
100 Grid Points</td></tr>
</table>

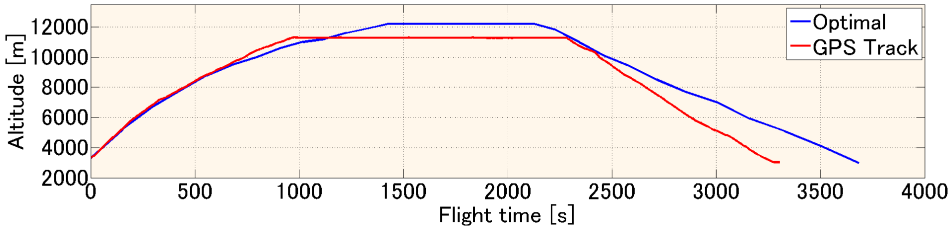
Reference Data List

Date (YY/MM/DD)	Departure / Arrival	Flight Time (JST)
2011/06/18	FUK / HND	14:02 / 15:20
2011/06/19	HND / FUK	20:00 / 21:48
2011/06/26	HND / FUK	19:58 / 21:28
2011/07/31	HND / FUK	19:59 / 21:30
2011/08/28	HND / FUK	18:50 / 20:31
2011/09/02	FUK / HND	09:53 / 11:30
2011/09/24	FUK / HND	10:57 / 12:20
2011/10/01	FUK / HND	15:04 / 16:22
2011/10/02	HND / FUK	19:54 / 21:41
2011/10/08	FUK / HND	16:11 / 17:29
2011/10/10	HND / FUK	11:22 / 12:59
2011/10/15	FUK / HND	16:04 / 17:42
2011/10/17	HND / FUK	10:20 / 12:00
2011/10/21	FUK / HND	9:55 / 11:20

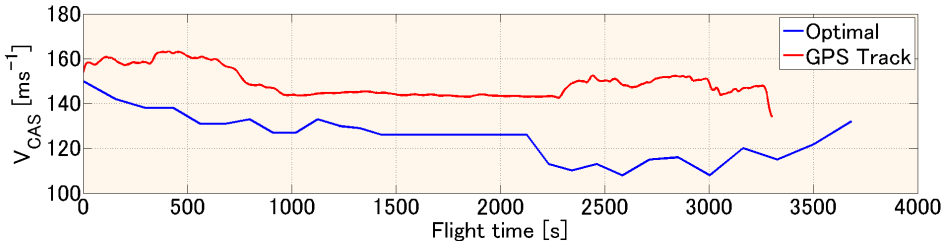
- Boundary values: Identical 3D-position and Calibrated Airspeed
- Initial mass of aircraft: Reference mass from BADA model
- Aircraft configuration: Clean Configuration of a twin engine wide body jet aircraft

- Application example (1) -

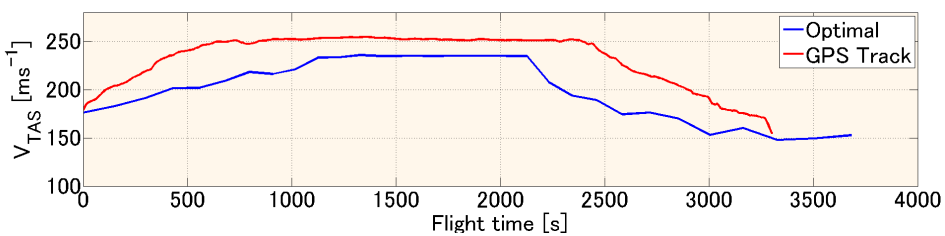
[Date: 2011/10/08] FUK→HND



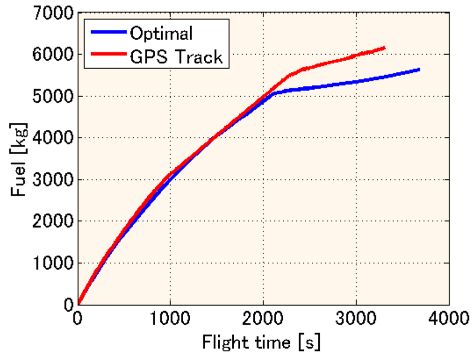
Altitude



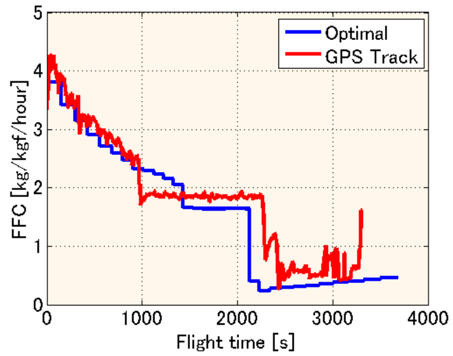
Calibrated Airspeed



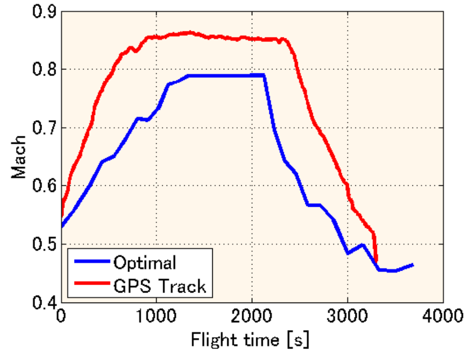
True Airspeed



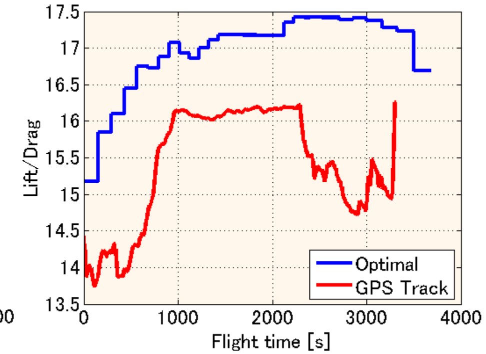
Fuel Consumption



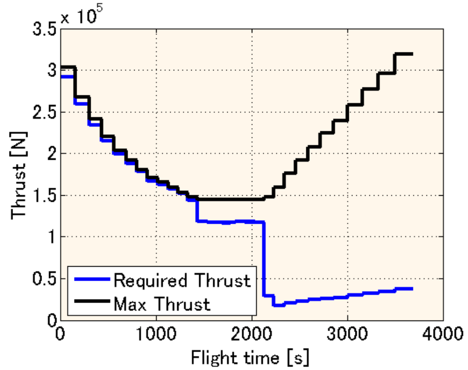
Fuel Flow



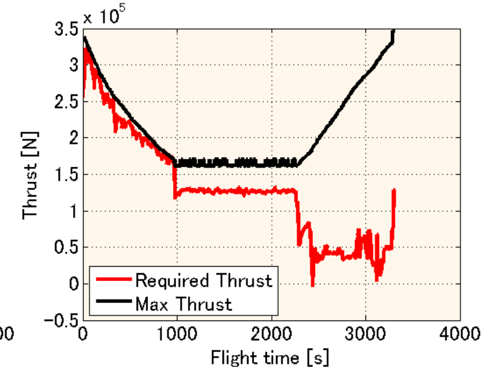
Mach Number



Lift Drag Ratio

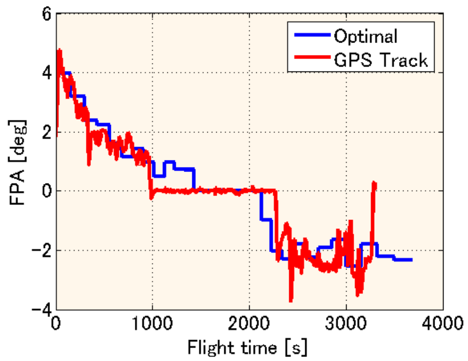


Thrust for Optimal Route

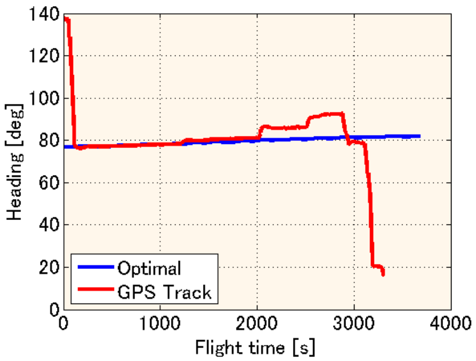


Thrust for GPS Route

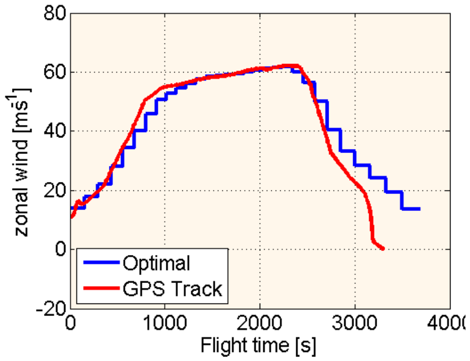
- Application example (1) -



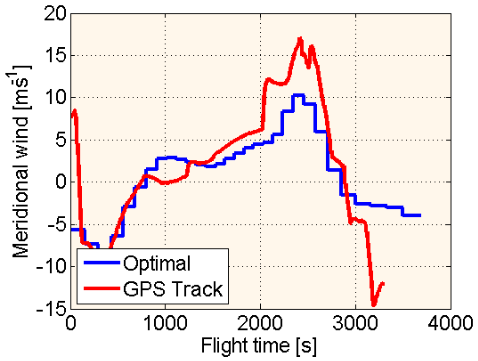
Flight Path Angle



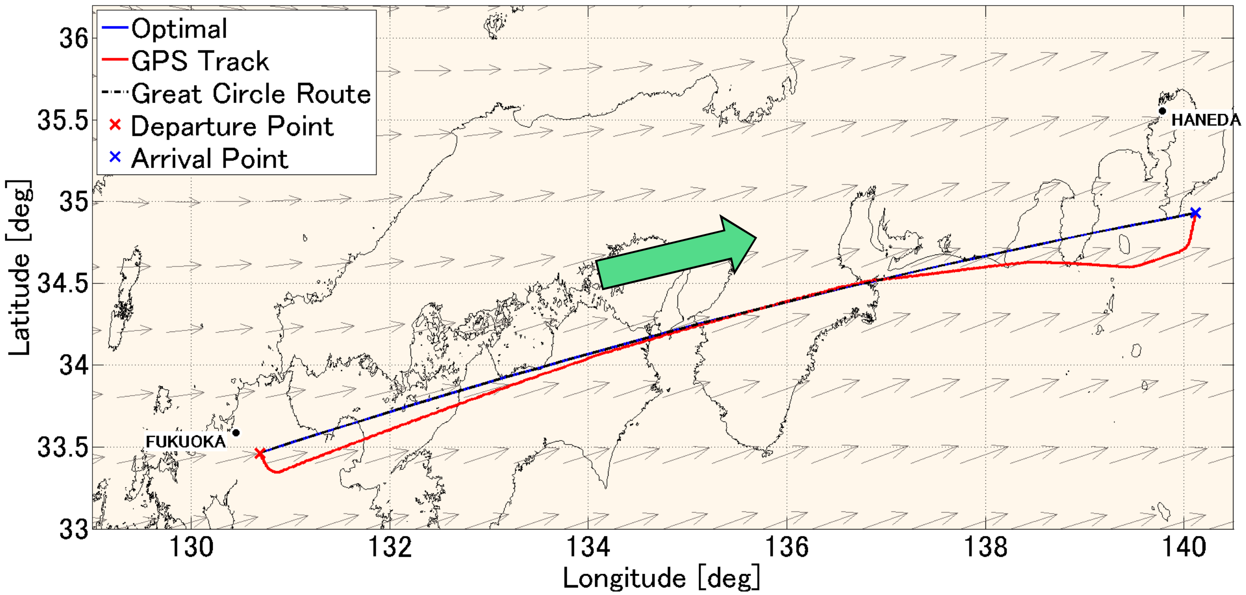
Heading Angle



Downrange Wind



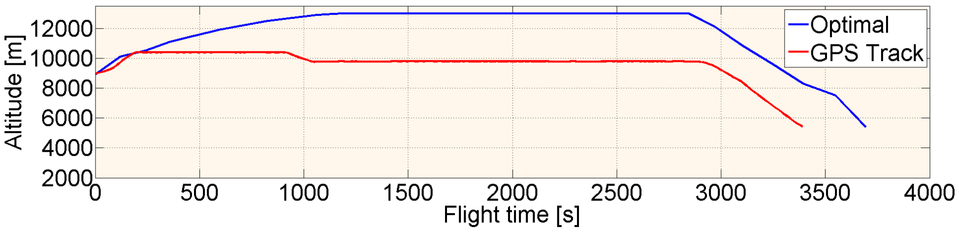
Cross range Wind



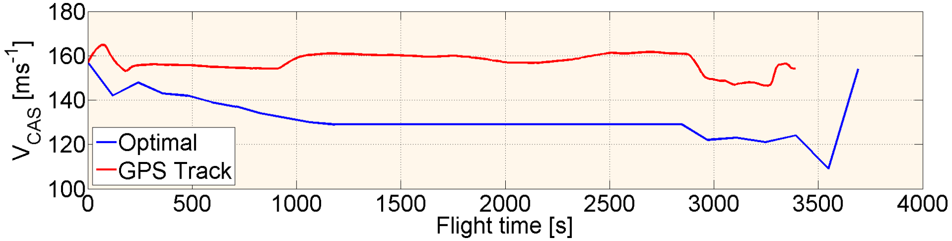
Lateral Flight Profile

- Application example (2) -

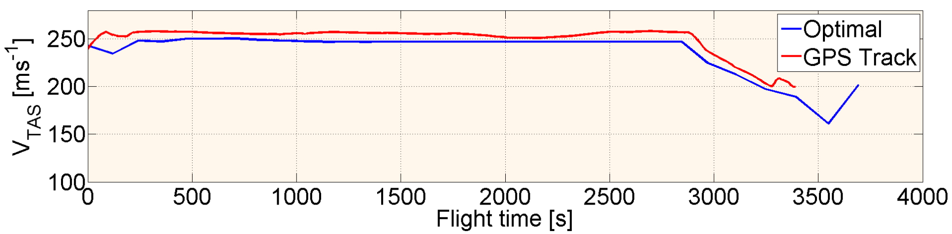
[Date: 2011/06/19] HND→FUK



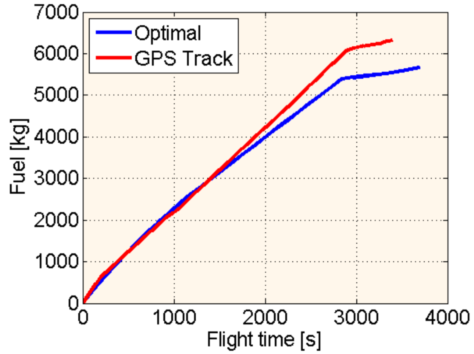
Altitude



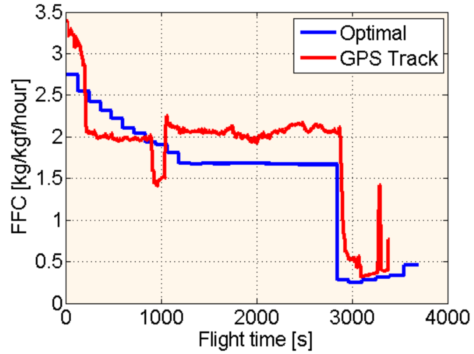
Calibrated Airspeed



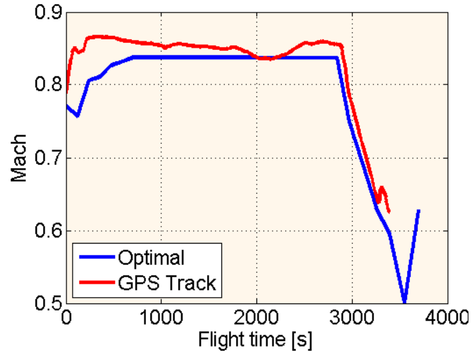
True Airspeed



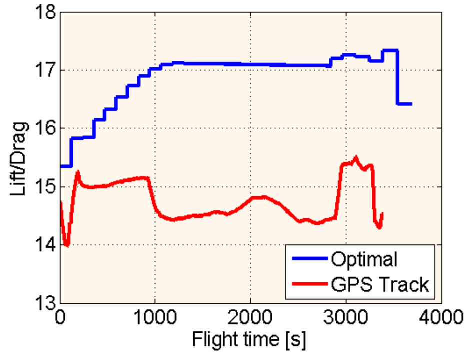
Fuel Consumption



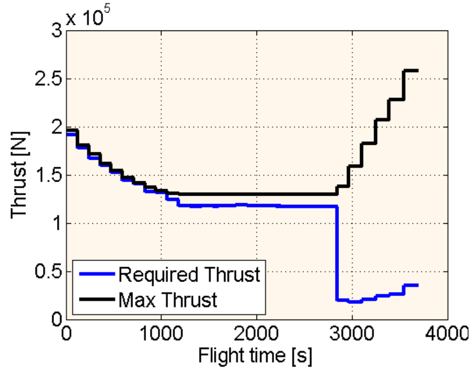
Fuel Flow



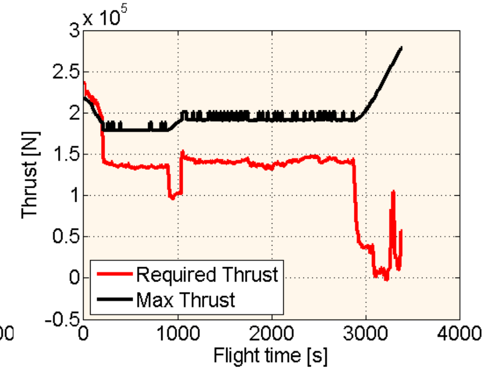
Mach Number



Lift Drag Ratio

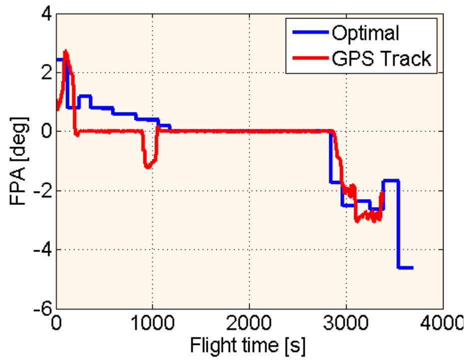


Thrust for Optimal Route

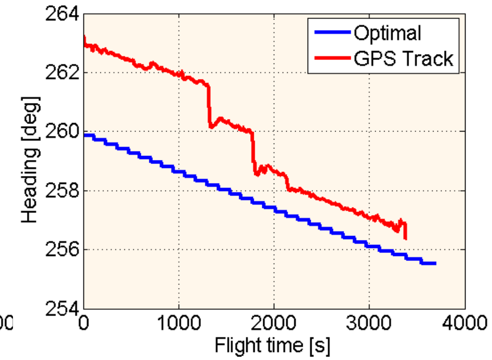


Thrust for GPS Route

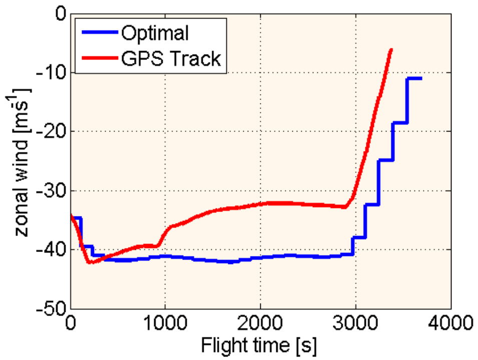
- Application example (2) -



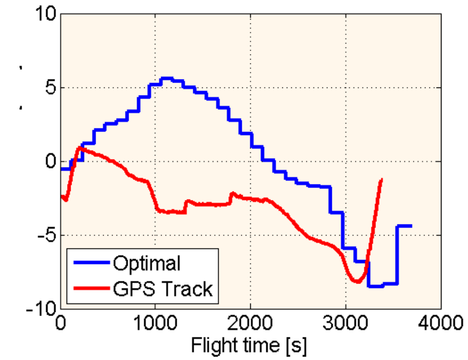
Flight Path Angle



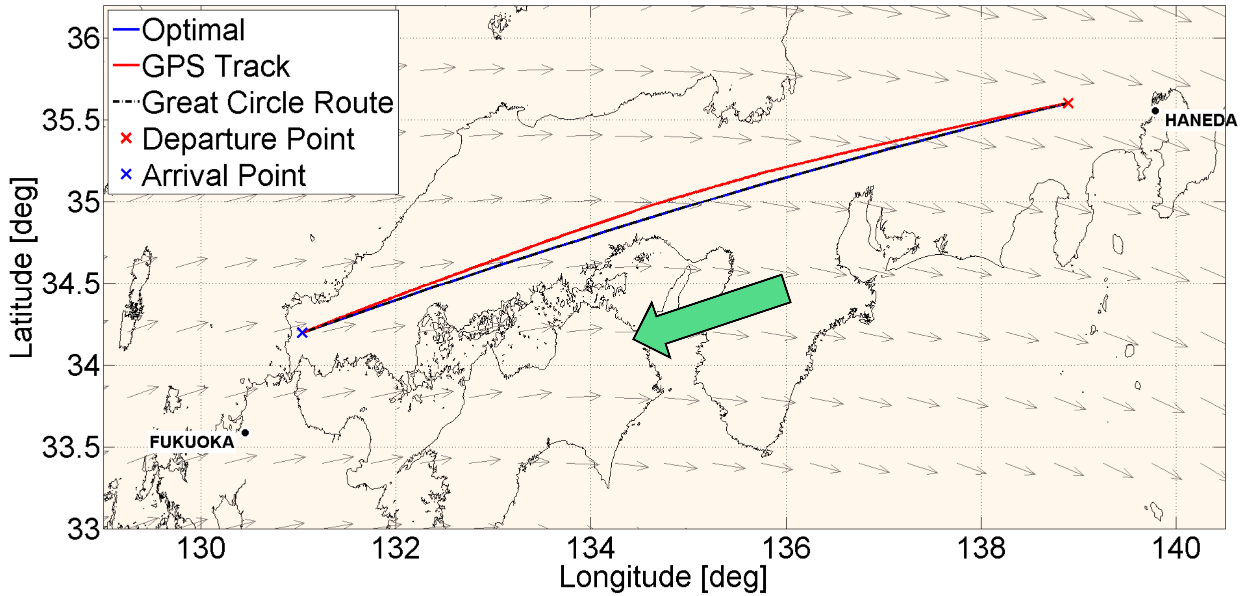
Heading Angle



Downrange Wind



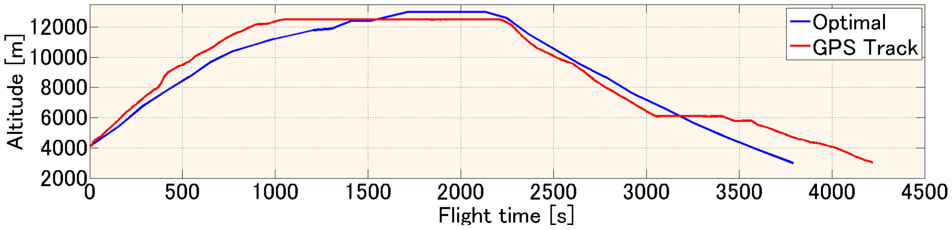
Cross range Wind



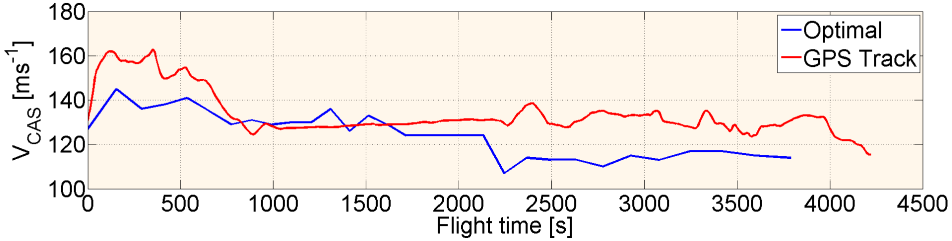
Lateral Flight Profile

- Application example (3) -

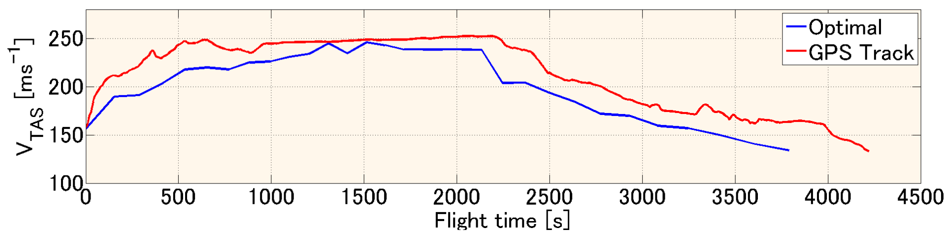
[Date: 2011/10/15] FUK→HND



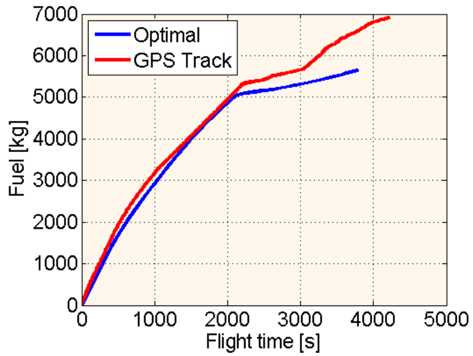
Altitude



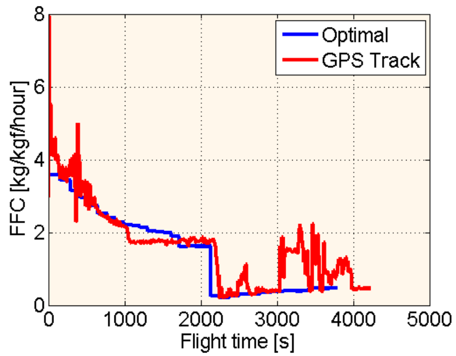
Calibrated Airspeed



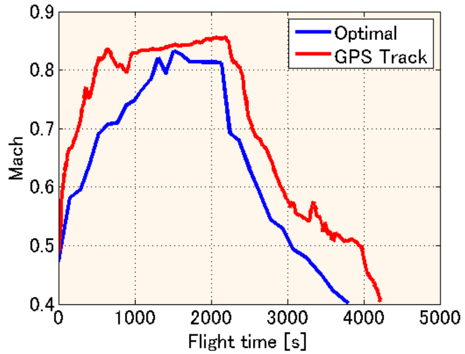
True Airspeed



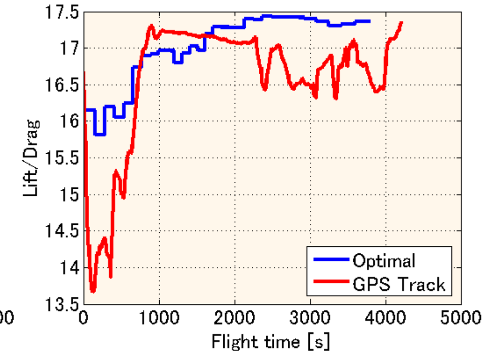
Fuel Consumption



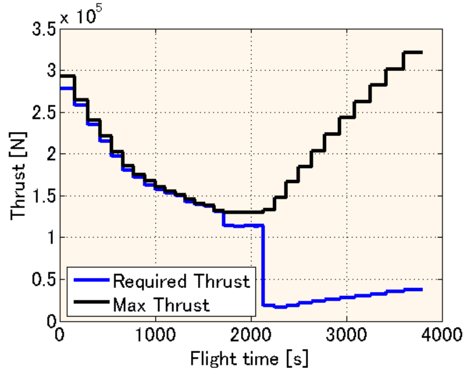
Fuel Flow



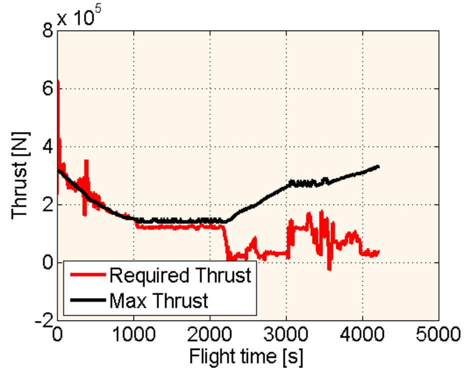
Mach Number



Lift Drag Ratio

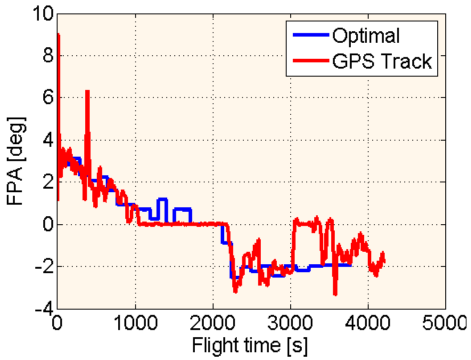


Thrust for Optimal Route

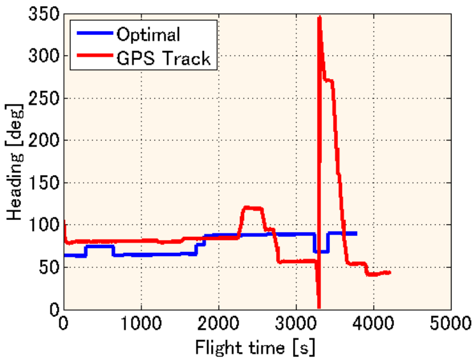


Thrust for GPS Route

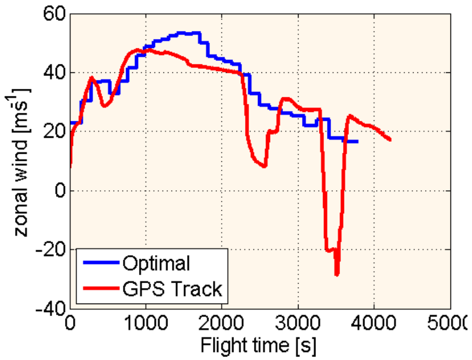
- Application example (3) -



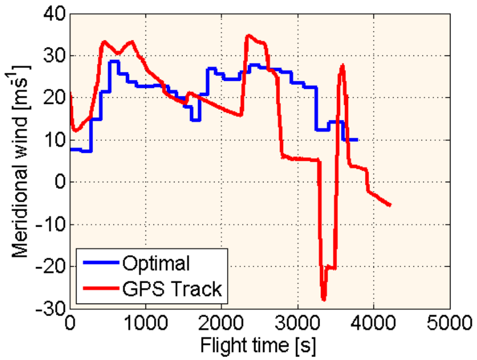
Flight Path Angle



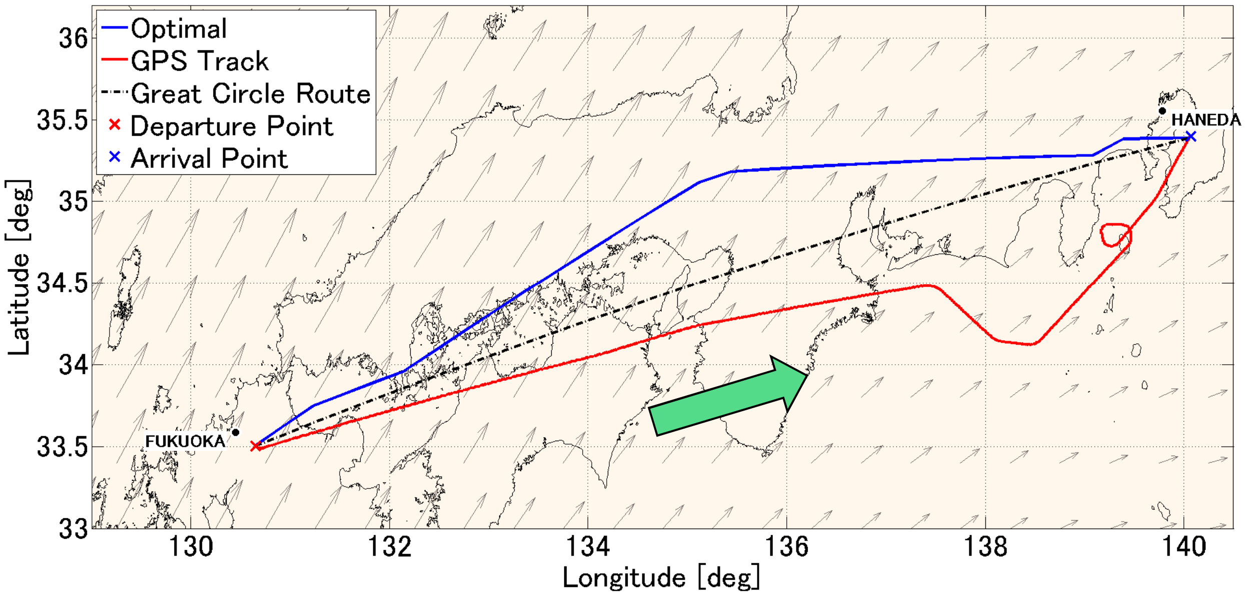
Heading Angle



Downrange Wind

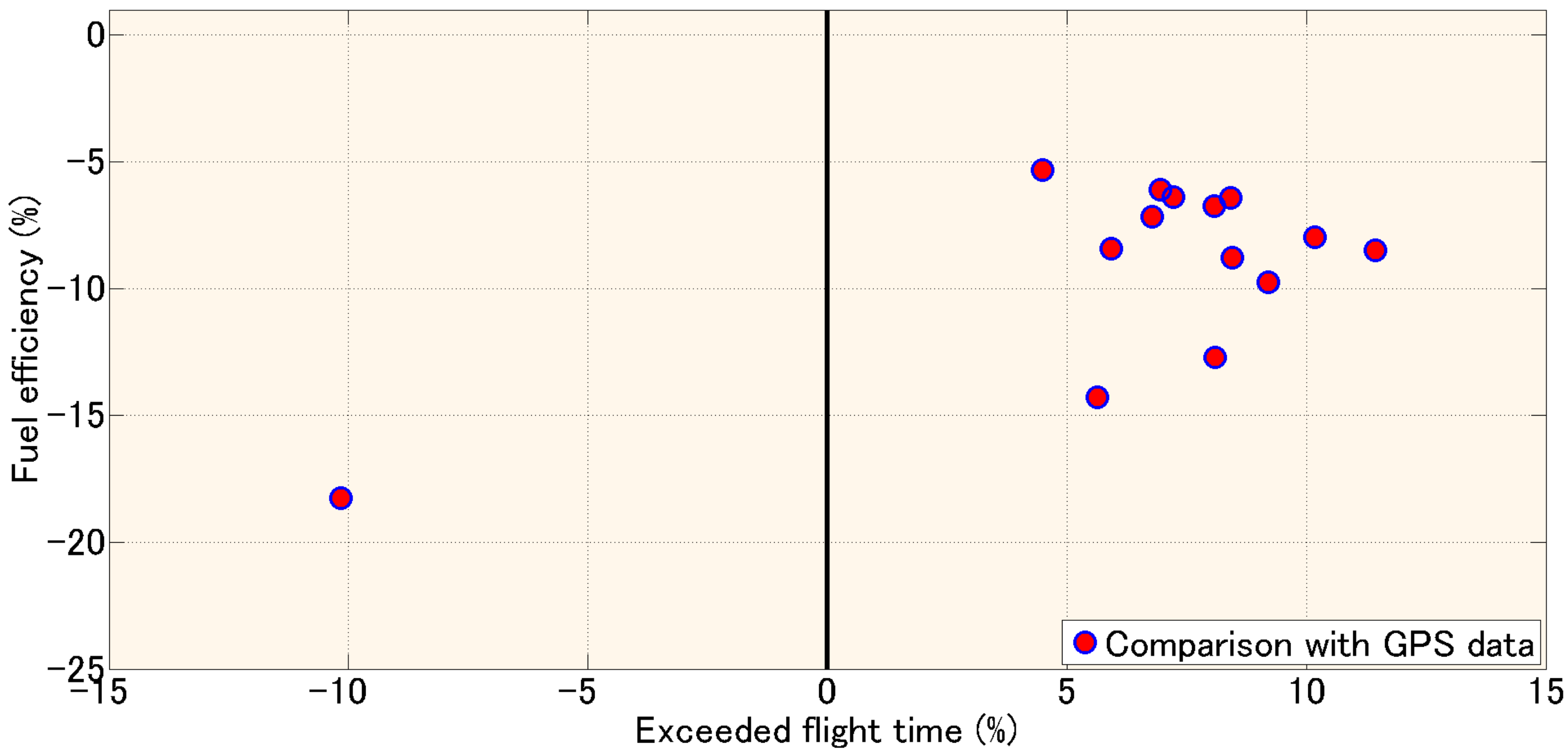


Cross range Wind



Lateral Flight Profile

- Quantitative Evaluation Results -

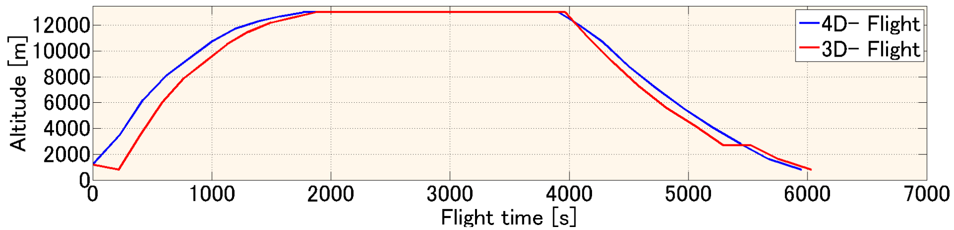


Tradeoff between Fuel Consumption and Flight Time

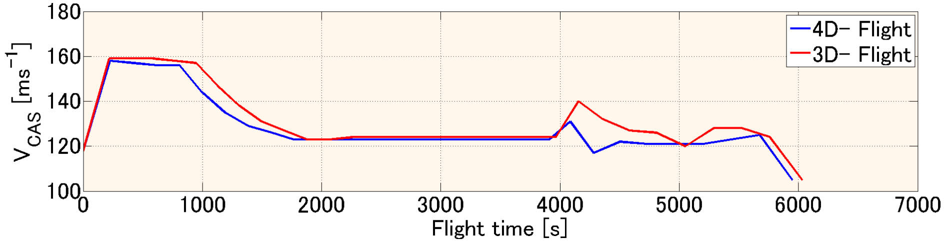
Average fuel consumption efficiency: -10%
Average exceeding flight time: 5%

- Effect of Wind Shear -

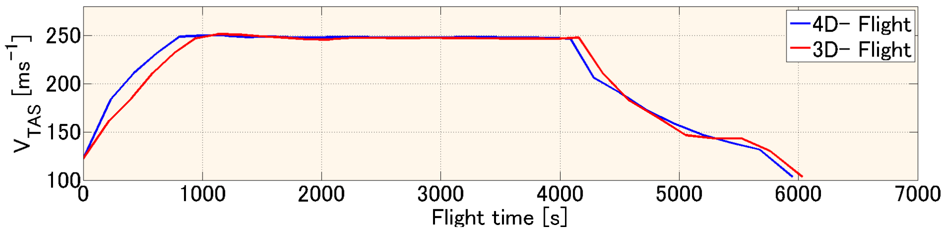
[Date: 2011/12/17] HND→FUK



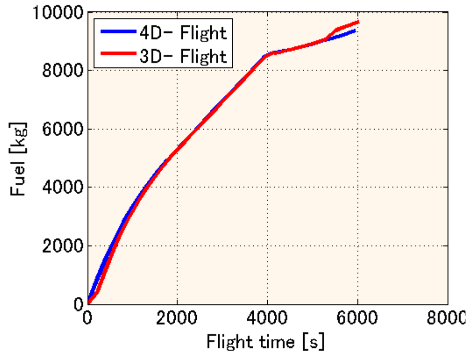
Altitude



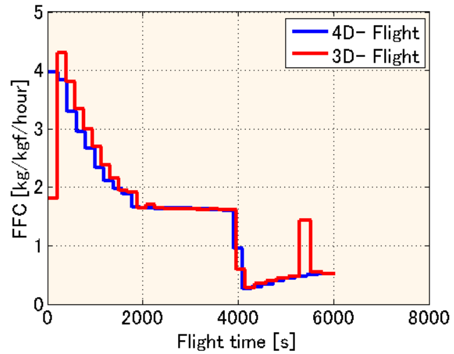
Calibrated Airspeed



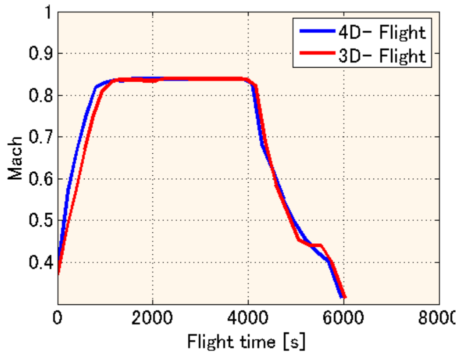
True Airspeed



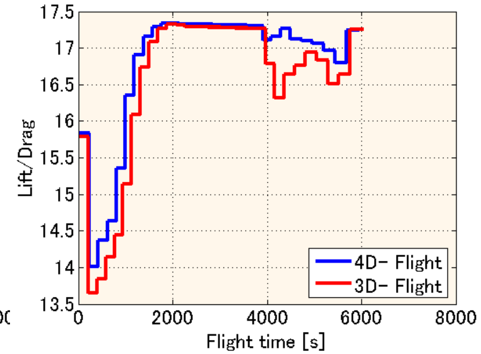
Fuel Consumption



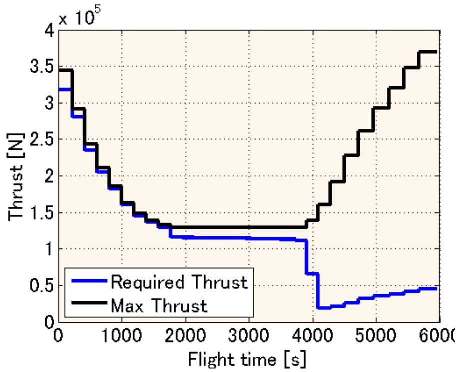
Fuel Flow



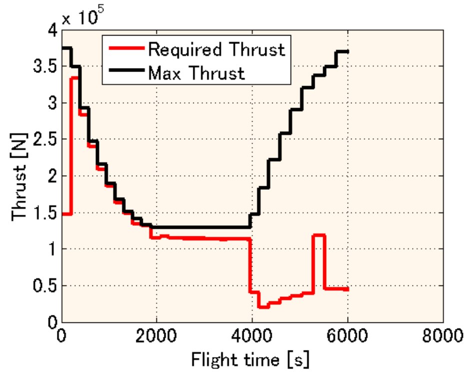
Mach Number



Lift Drag Ratio

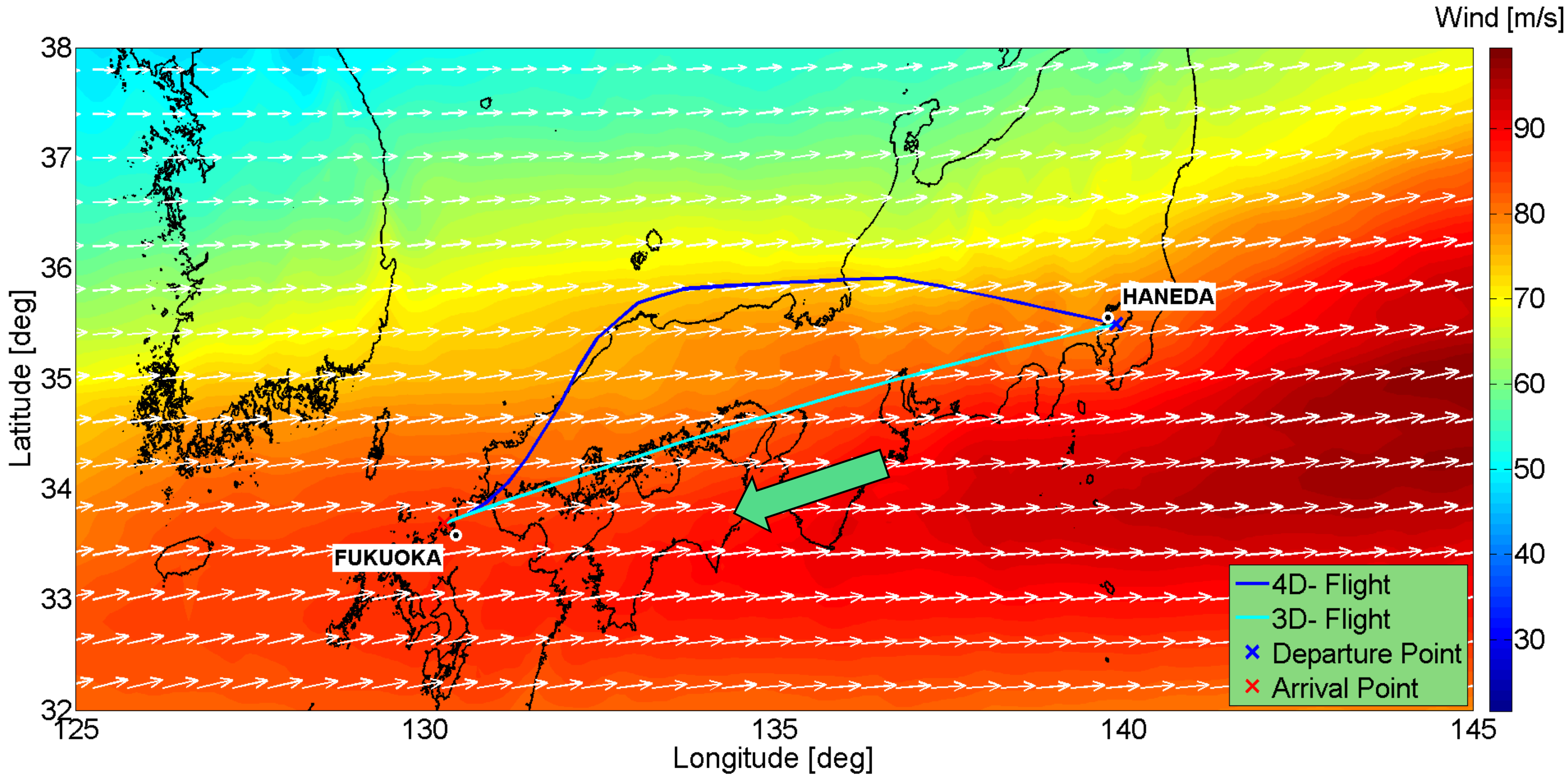


Thrust for 4D Route



Thrust for 3D Route

- Effect of Wind Shear -



Lateral Flight Profile Comparison

<u>3D- Optimal Route</u>
Fuel Consumption : 9651.08[kg]
Flight Time : 6031[sec]

⇔

<u>4D- Optimal Route</u>
Fuel Consumption : 9349.9[kg]
Flight Time : 5948[sec]

- Conclusions -

- Flight trajectory optimization plays an important role in the development of a futuristic ATS system and optimized flight trajectories in presence of winds would greatly increase the benefits such as fuel consumption of modern jet passenger aircraft.

- **Dynamic Programming Method** is introduced as an optimization tool for flight trajectory optimization. → **Reference: EN-040**

- Numerical weather prediction models provided **Weather Data** are highly accurate and can be well used to predict future weather conditions at flight planning.

- The used aircraft performance model, **BADA Model** possesses highly accurate aircraft performance data which can be used to evaluate fuel consumption.

- Using a simple GPS data logger to record a very few number of flight data parameters in an airliner cabin was sufficient to implement a substantial research and understand the structure of the ATC system. → **Reference: EN-039**

- An **average fuel efficiency of 5% ~ 10%** could be obtained by **choosing a lower descent speed and a smoother descent rate** with the application of Trajectory Based Operations.

- Overall optimization considering the **tradeoff of fuel consumption and flight time** would eventually contribute towards a futuristic Air Transportation System with great benefits.

Thank you for your kind attention.