[EN-103] Development of Trajectory Prediction Model

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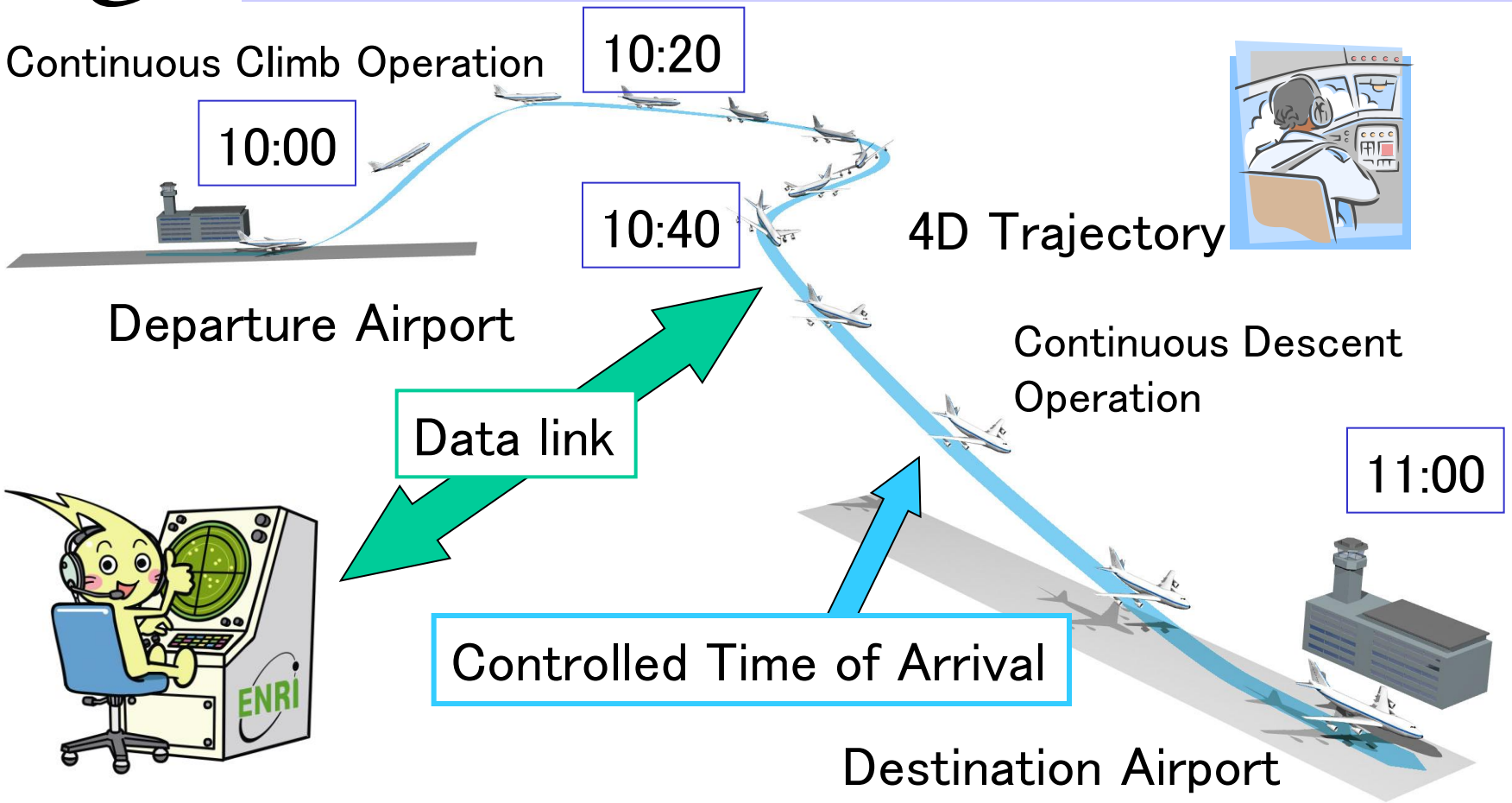
Trajectory Based Operation



- Trajectory : A description of the movement of an aircraft, both in the air and on the ground, including position, time and, at least via calculation, speed and acceleration. (ICAO Doc 9854)

Future Vision

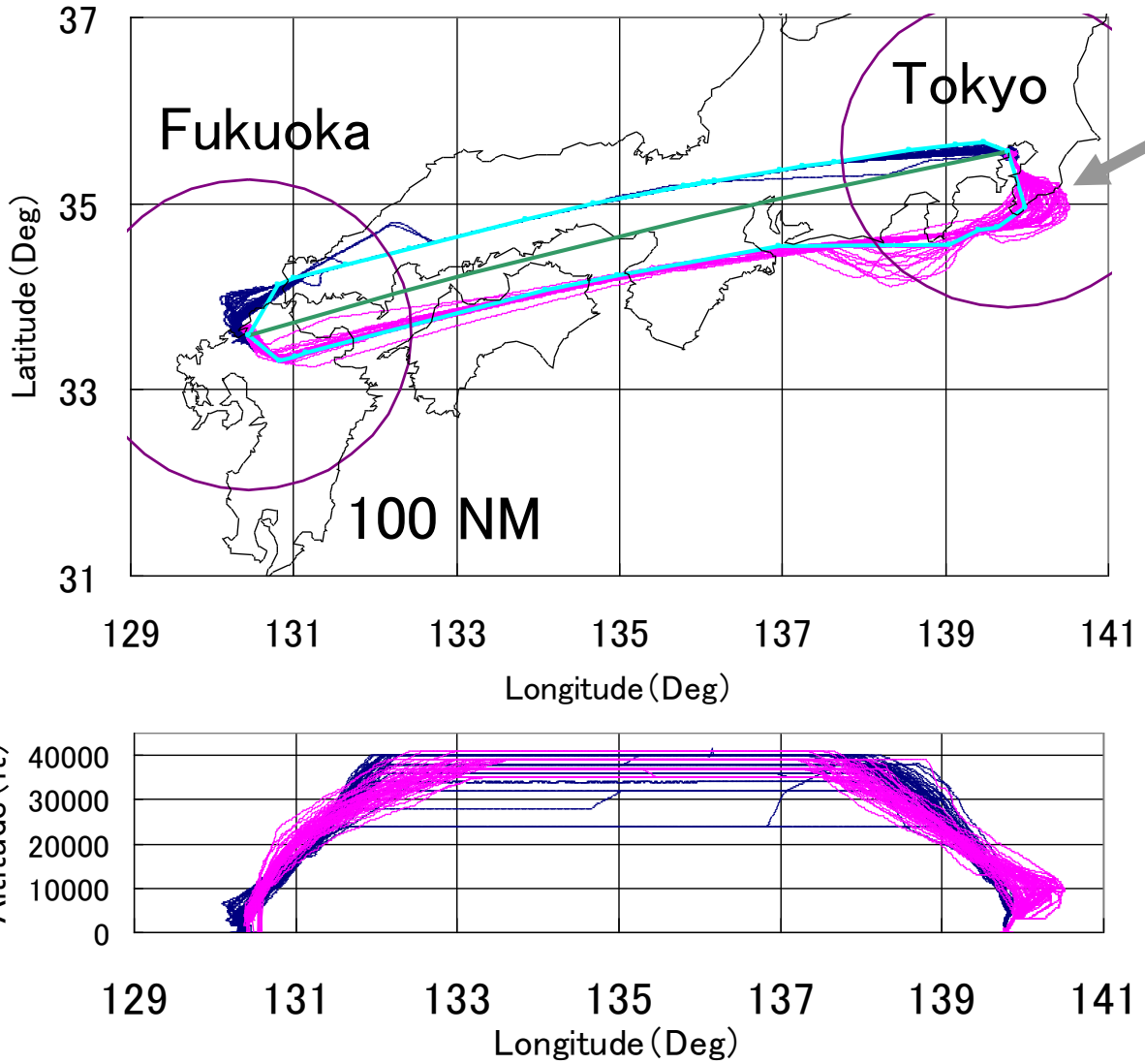
- Trajectory based operation is a key operational concept in future vision.
  - Global ATM operational concept (ICAO)
  - NextGen : Next Generation Air Transportation System) (USA)
  - SESAR : Single European Sky ATM Research (EUROCONTROL)
  - CARATS : Collaborative Actions for Renovation of Air Traffic Systems (Japan Civil Aviation Bureau)
  - ENRI long term research vision

Technology Development

- Optimization and control of one aircraft
  - Managed by FMS (Flight Management System)
  - Flight Time, Fuel: RNAV, RNP
- Optimization and control of all aircraft
  - Ground based trajectory prediction and control system is required for all aircraft.
  - Conflict Detection, CTA (Controlled Time of Arrival) Assignment, Trajectory Coordination

RNAV: Area Navigation
RNP: Required Navigation Performance

Actual Trajectory Examples



Flight path extension near destination airport because of traffic congestion.

Blue:
Tokyo -> Fukuoka
Red:
Fukuoka -> Tokyo
Light Blue:
Flight Plan Route

Trajectory Prediction Model

Airline Operation Model
- Altitude
- Speed
- Weight

Navigation Database
- Lat. Lon. of Waypoints
- Route
- Dept./Arv. Route

Aircraft Performance Data
- Flight Envelope
- Aerodynamics

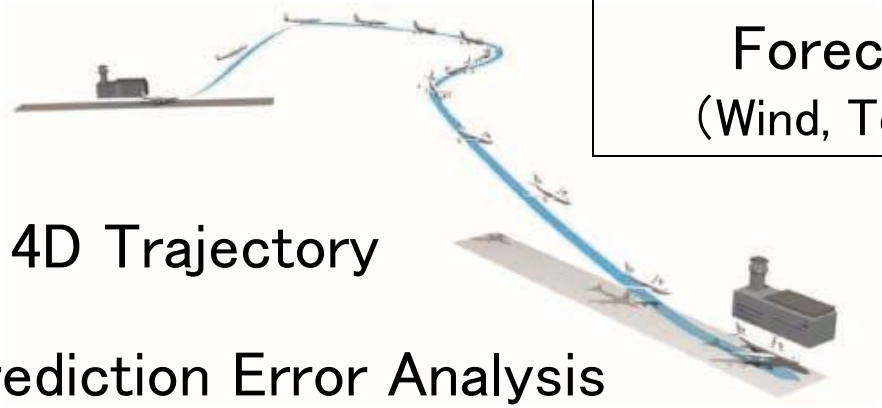
Energy Condition

$$(T - D)\,V_{TAS} = mg\frac{dh}{dt} + mV_{TAS}\frac{V_{TAS}}{dt}$$

Trajectory Predictor

Surveillance Data

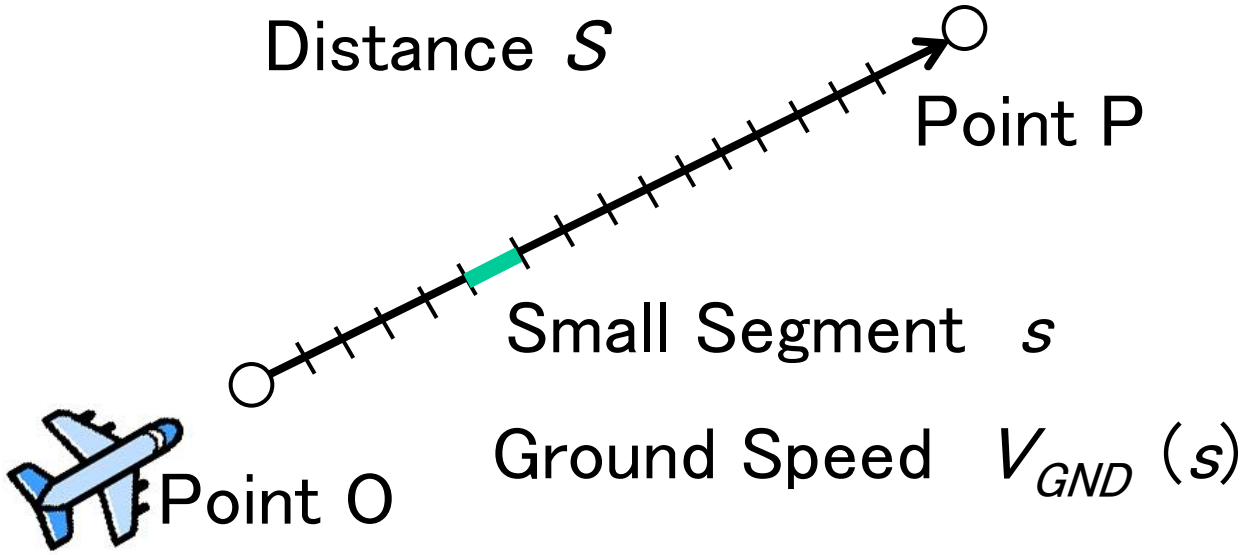
Weather Forecast
(Wind, Temp.)



Actual Trajectory ⟺ 4D Trajectory

Evaluation, Prediction Error Analysis

Flight Time Calculation



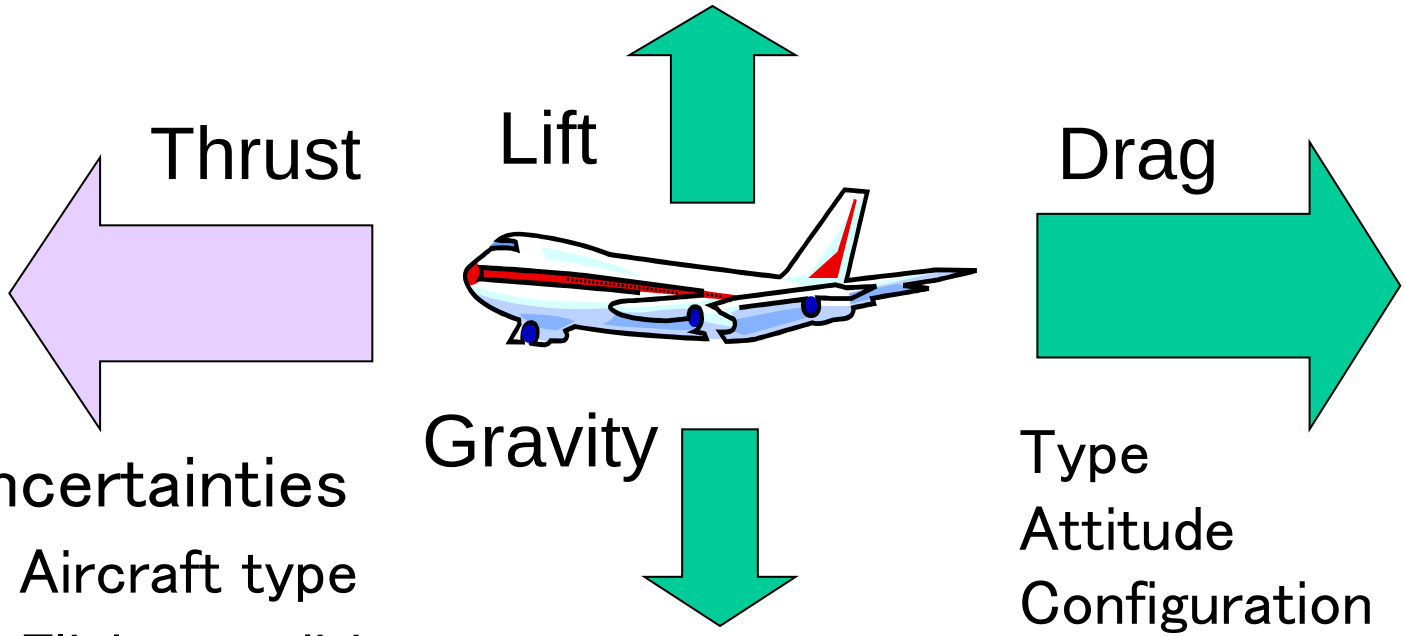
Flight time from O to P

＝Sum of small segment flight time ($s / V_{GND}(s)$)

$$T_p = \int_0^S \frac{1}{V_{GND}(s)} ds$$

Prediction Model

- Total Energy Model (Point-Mass Model)



- Uncertainties
  - Aircraft type
  - Flight condition
  - Pilot operation
  - ATC instructions
  - Meteorological conditions

Type
Attitude
Configuration

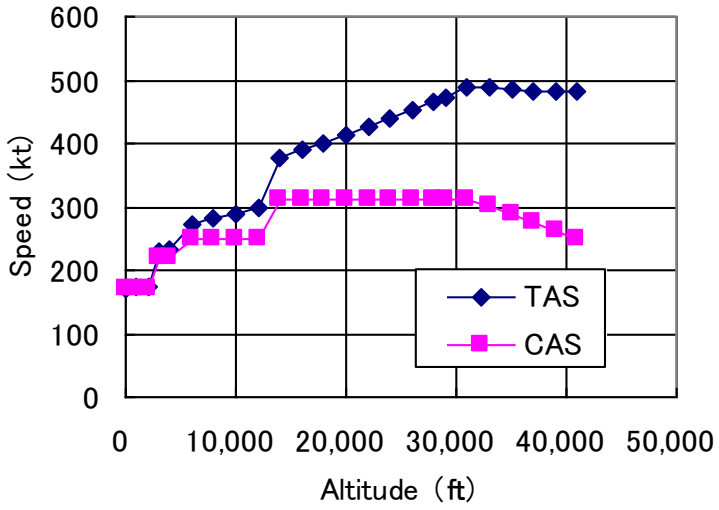
$$(T - D)\, V_{TAS} = mg \frac{dh}{dt} + mV_{TAS} \frac{V_{TAS}}{dt}$$

Prediction Method

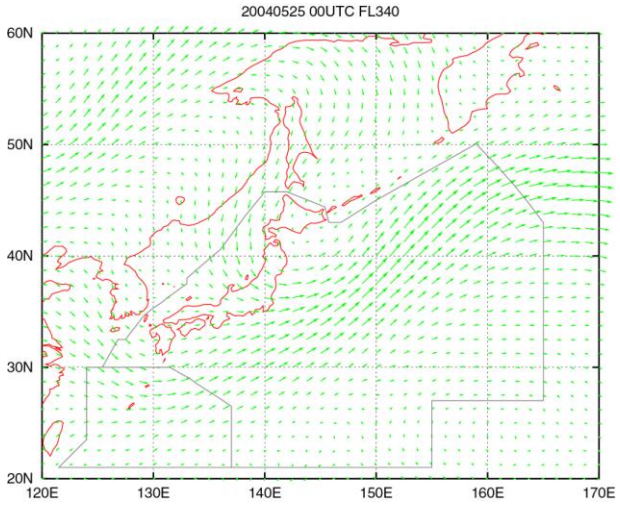
- Speed estimation is important for time prediction.

Calibrated Air Speed (CAS)	→	True Air Speed (TAS)	→	Ground Speed (GS)

Air Density

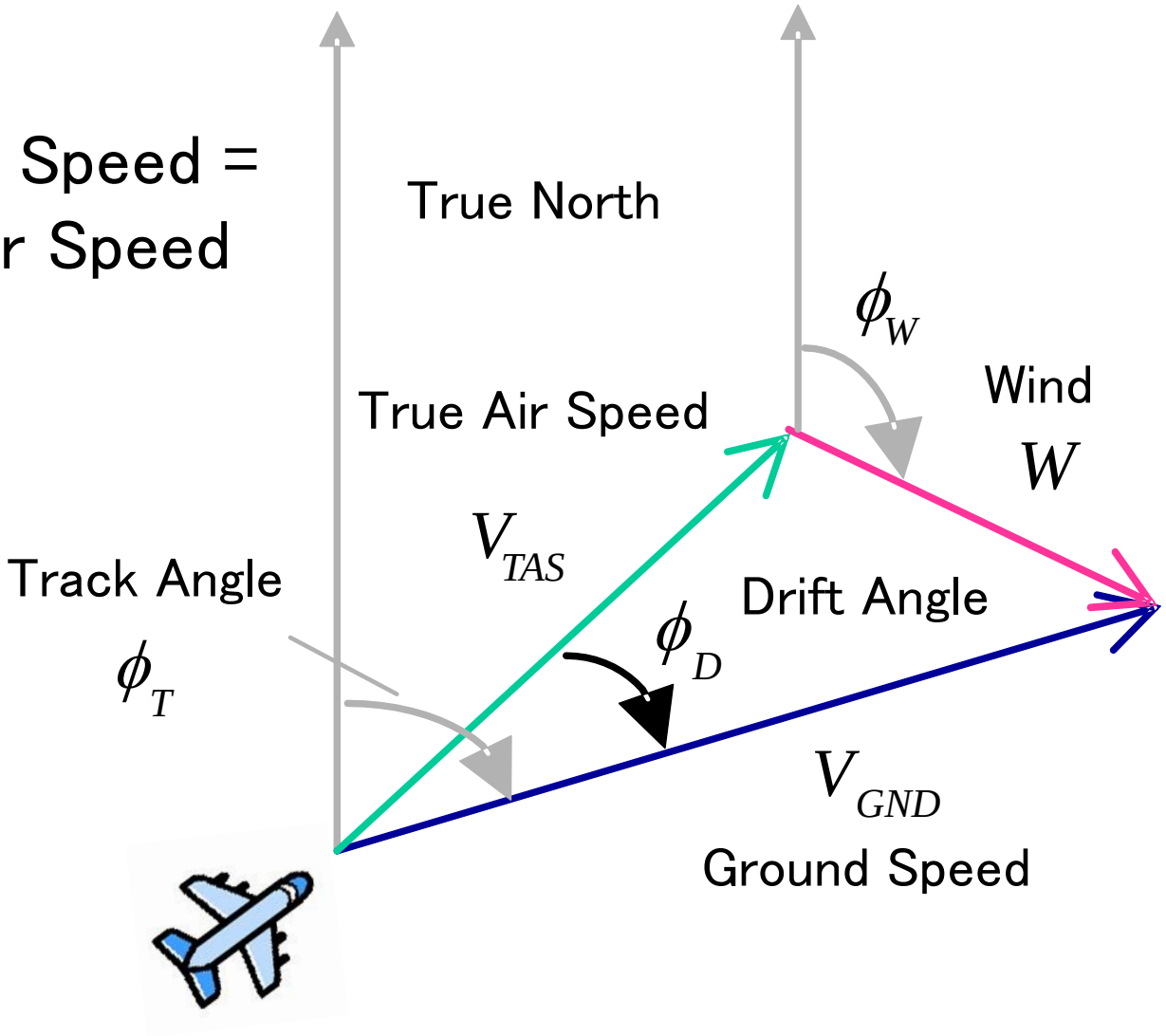


+Wind



Ground Speed Calculation

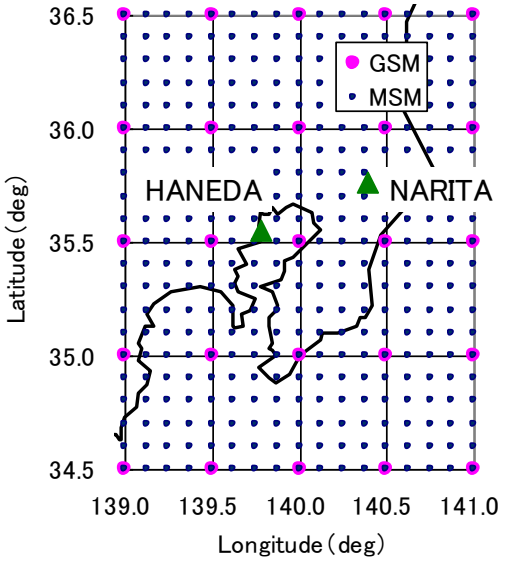
Ground Speed =
True Air Speed
+ Wind



Prediction Data

- Aircraft Performance Model
  - BADA (Base of Aircraft Data) of EUROCONTROL
- Meteorological Forecast
  - JMA (Japan Meteorological Agency), GSM, MSM

Model Name	GSM	MSM (GPV)
Area	Global scale	Meso scale
Area	Global Earth	Japan
Update cycle	6 hour	3 hour
Grid	0.5 deg	0.125/0.1 deg
Vertical	1,000hPa (364ft) – 100hPa (53,083ft), 12 layer	

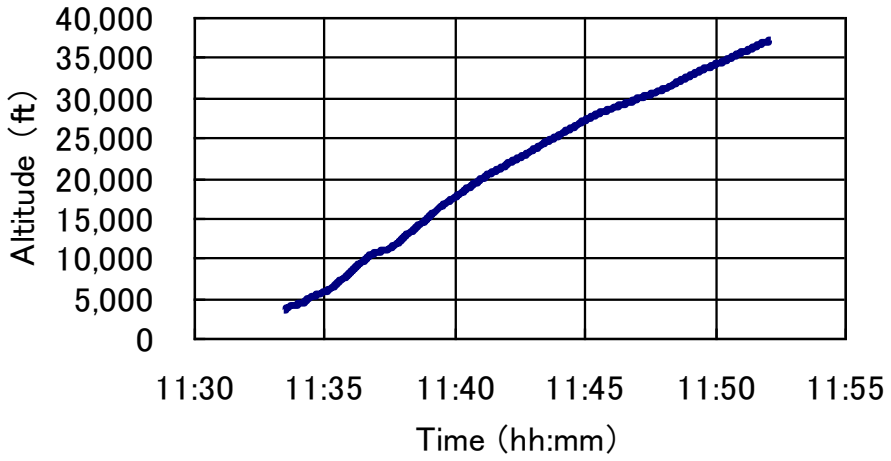


Comparison Methods

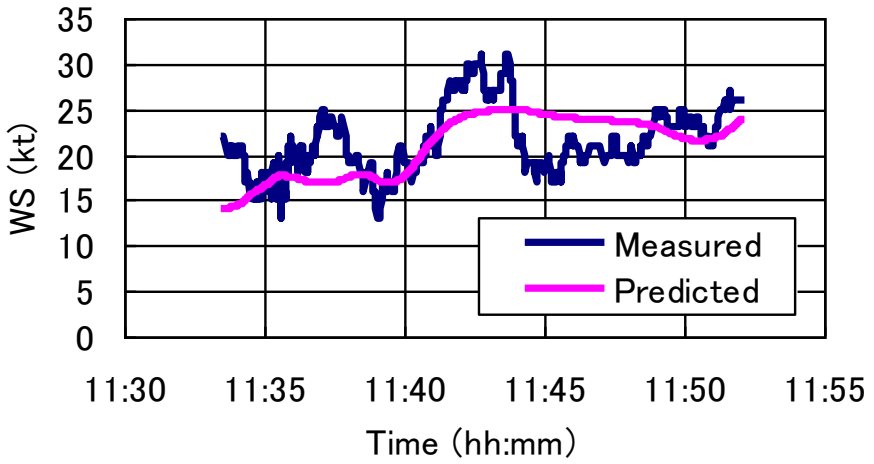
Weather Forecast	♦Measured data by aircraft ♦Predicted data by interpolation of numerical forecast (MSM)
Aircraft Speed	♦Measured data by aircraft ♦Predicted data with BADA speed model

Comparison of Climb

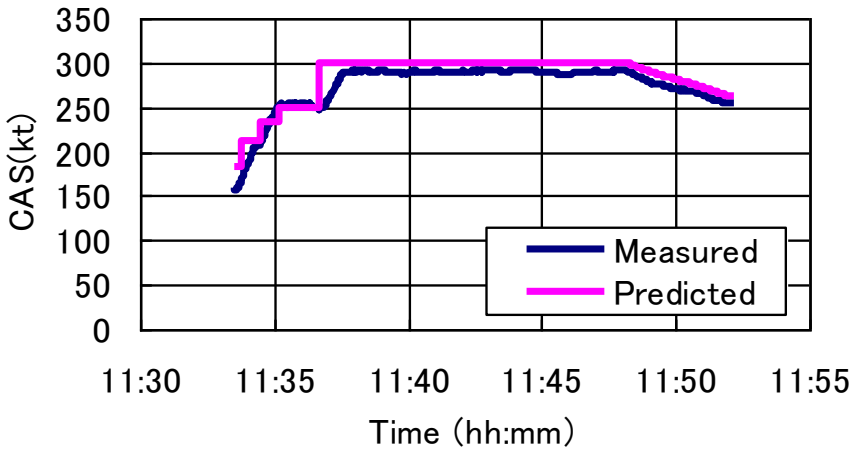
Altitude



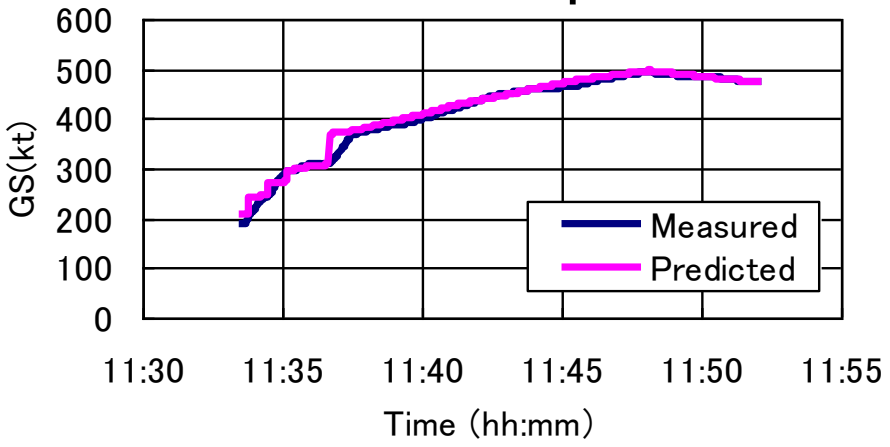
Wind Speed



CAS

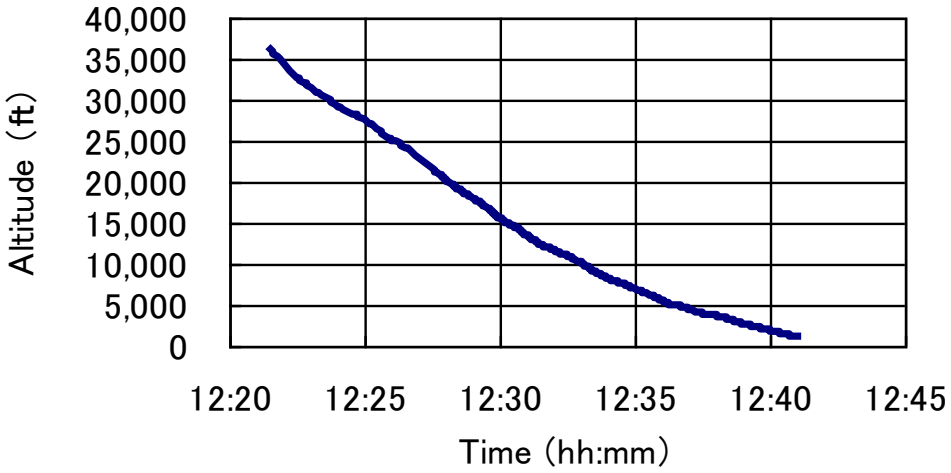


Ground Speed

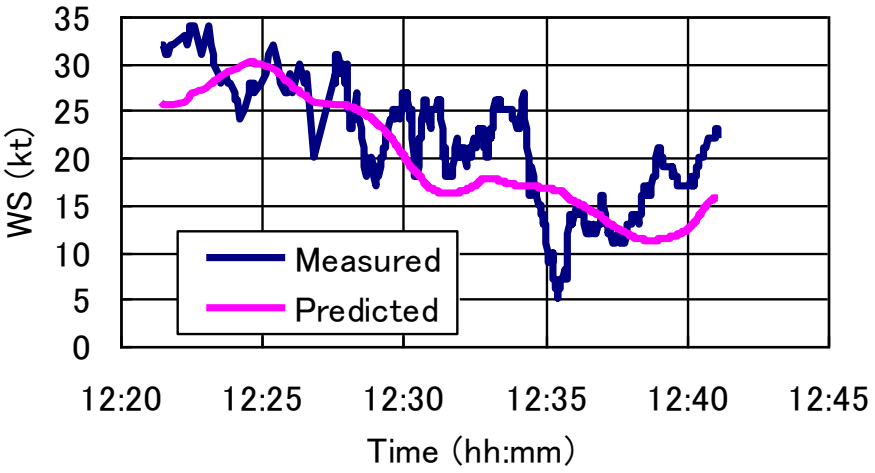


Comparison of Descent

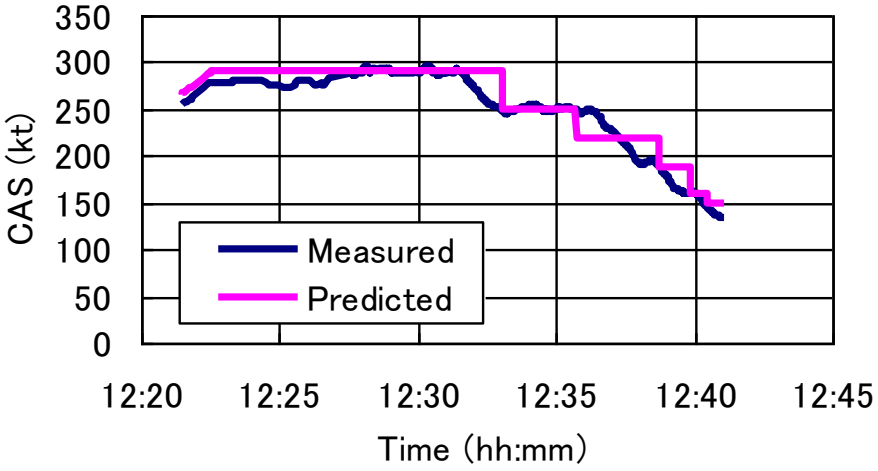
Altitude



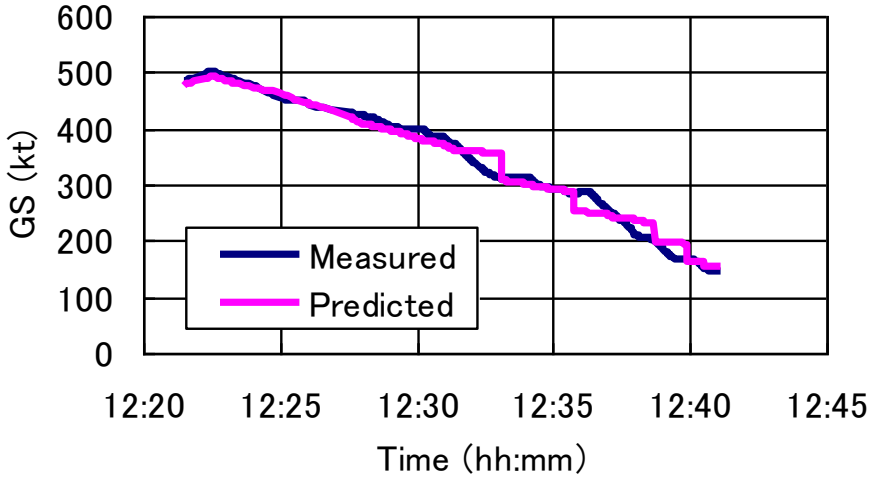
Wind Speed



CAS



Ground Speed



Error Factors of Ground Speed

Ground Speed　Wind Speed　Wind Direction

$$dV_{GND} = \frac{\partial V_{GND}}{\partial W} dW + \frac{\partial V_{GND}}{\partial \phi_W} d\phi_W$$

$$+ \frac{\partial V_{GND}}{\partial V_{TAS}} dV_{TAS} + \frac{\partial V_{GND}}{\partial \phi_T} d\phi_T$$

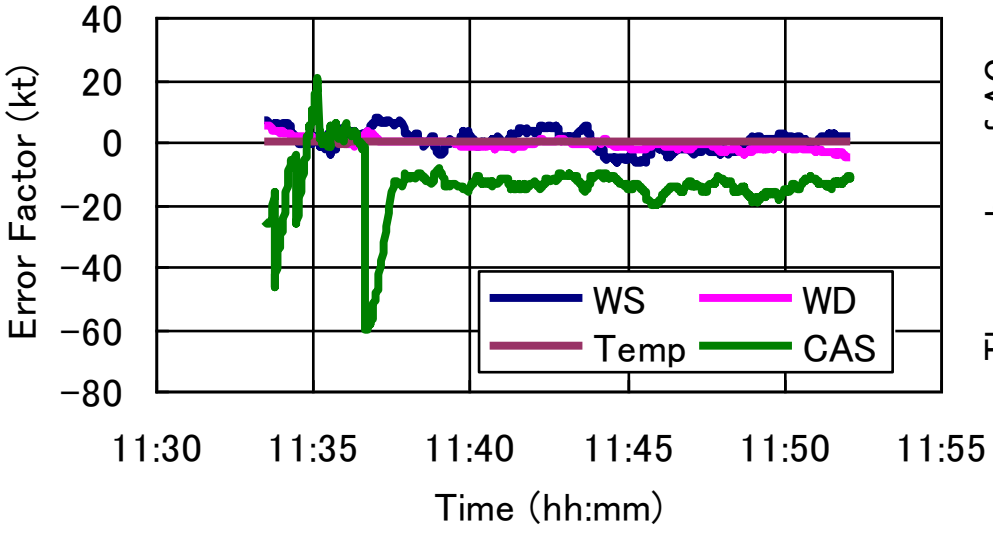
True Air Speed
（Mach、CAS、Temperature）

Track Angle

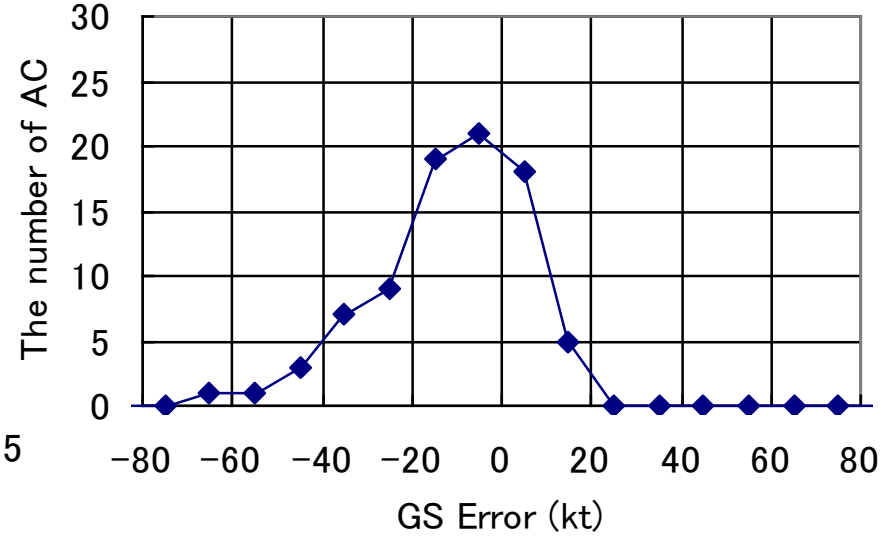
- Partial Derivative Coefficient：
  Degree of Influence of Each Factor
- Total Derivative of Factor： Error of Each Factor

Prediction Error in Climb

Error Factor



GS Error Distribution

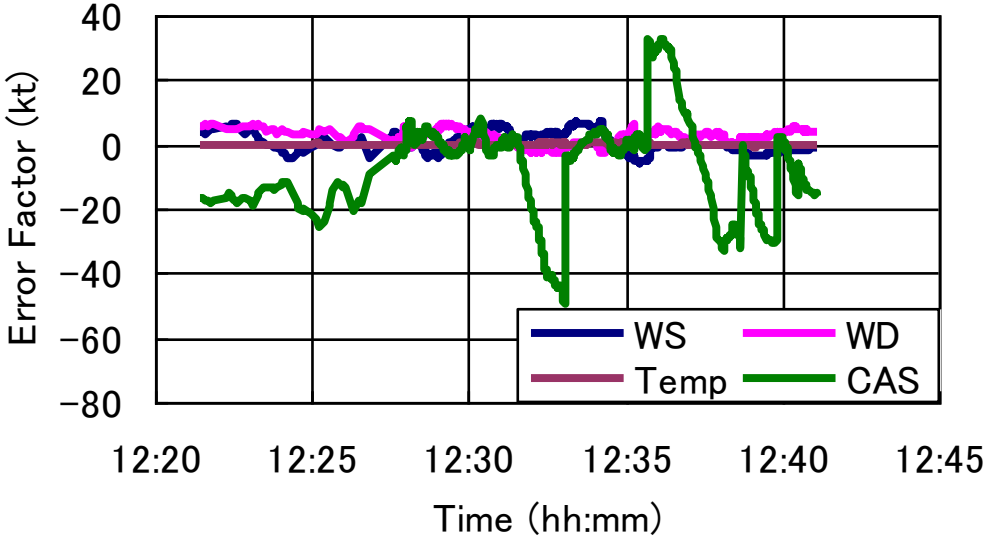


Average GS Error : −5.3 kt

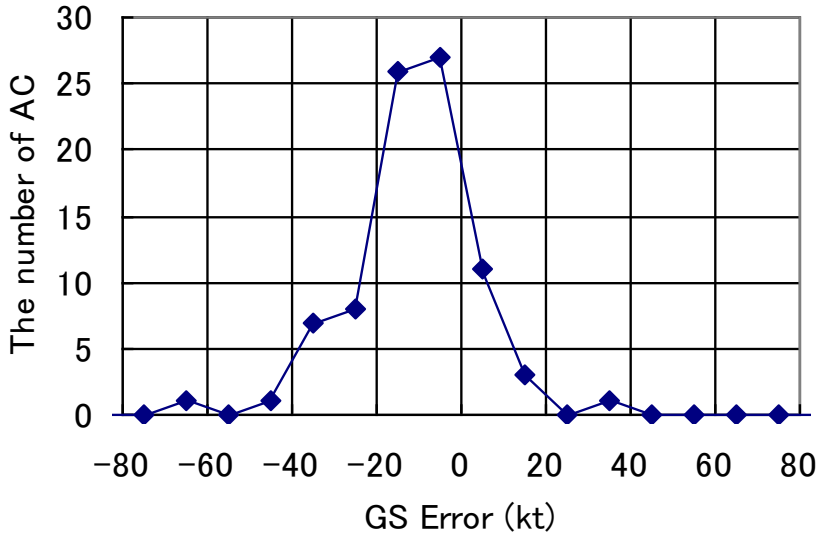
84 aircraft

Prediction Error in Descent

Error Factor



GS Error Distribution



Average GS Error : 0.44 kt

85 aircraft

Summary

- ENRI is developing the trajectory prediction model for trajectory based operation.
- Error factors due to the aircraft speed model and error factors due to weather forecasts were analyzed for Ground Speed (GS) prediction.
- Aircraft speed model error was larger than weather forecast error in most cases.
- Measured GS is smaller than predicted GS.

Future Works

- Climb and descent rate analysis.
- Weather forecast error detailed analysis.
- Algorithm development to modify trajectory to resolve conflicts and meet CTA (Controlled Time of Arrival).