34th DASC
Digital Avionics Systems Conference

IEEE AESS AIAA DATC

Impact of Global Mandates on Avionics Research and Development

Corinthia Hotel
Prague, Czech Republic
13-17 September 2015

# Evaluation of in-flight trajectory optimisation with time constraints in a moving base flight simulator

**Xavier Prats**

*Technical University of Catalonia (UPC)*

Frank Bussink, Ronald Verhoeven and Adri Marsman

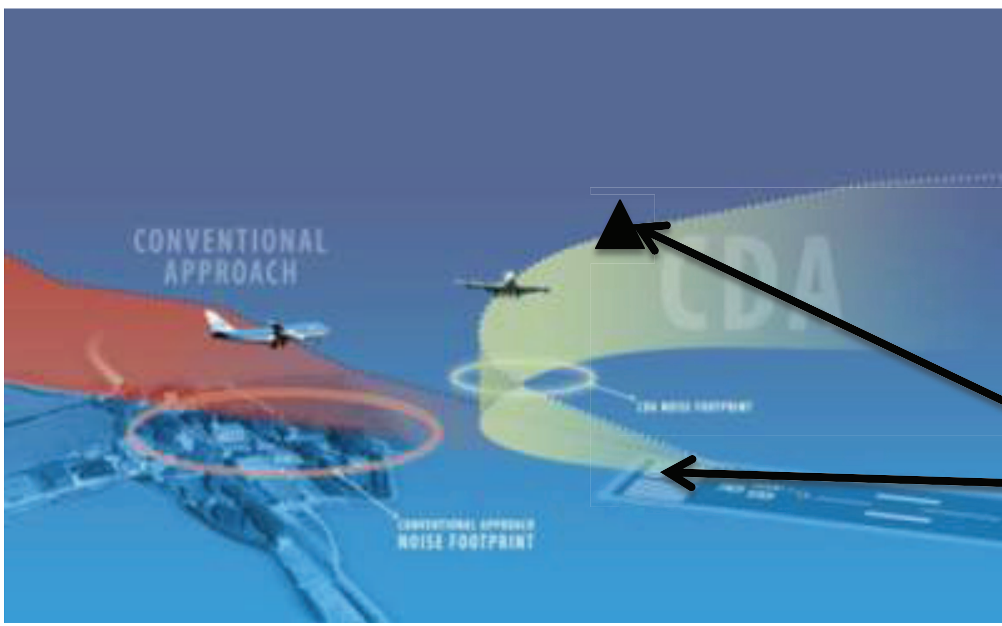
*National Aerospace Laboratory (NLR)*

CLEANSKY FASTOP Concorde

**FASTOP and CONCORDE projects** were partially funded from the European Union's 7th Framework Programe through the **Clean Sky** Joint Technology Initiative under Grant Agreements no. **CS-GA-2013-323495** and **CS-GA-2013-620130**, respectively.

# Introduction

- Continuous descent Operations (CDO) have shown important environmental benefits w.r.t. conventional (step-down) approaches.
- However, maintaining separation among aircraft becomes more difficult leading to important capacity reductions.
- At present, CDOs are mainly operational in low-density scenarios.




Possible solution to maintain capacity: Required Times of Arrival (RTA) given by ATC

# Introduction

## Time and Energy managed operations (TEMO)

- Onboard application, aiming to achieve environmentally friendly CDO in high-density terminal maneuvering areas (TMA).
- Meet Required Times of Arrival (RTA) at different waypoints minimizing the usage of throttle and speedbrakes.
- Optimized descent trajectory from the Top of Descent (TOD) until the runway threshold complying with the RTAs while minimizing fuel usage and noise (speedbrakes).
- Fixed RNAV/RNP route
- TEMO consists of a trajectory planning and an guidance module.

# TEMO

Trajectory Plan

## Planning Function

- An optimal control problem is solved
- Minimizing fuel and speedbrake usage, while fulfilling operational constraints (including RTAs)
- Produces a speed, thrust and speedbrake plan for the whole descent

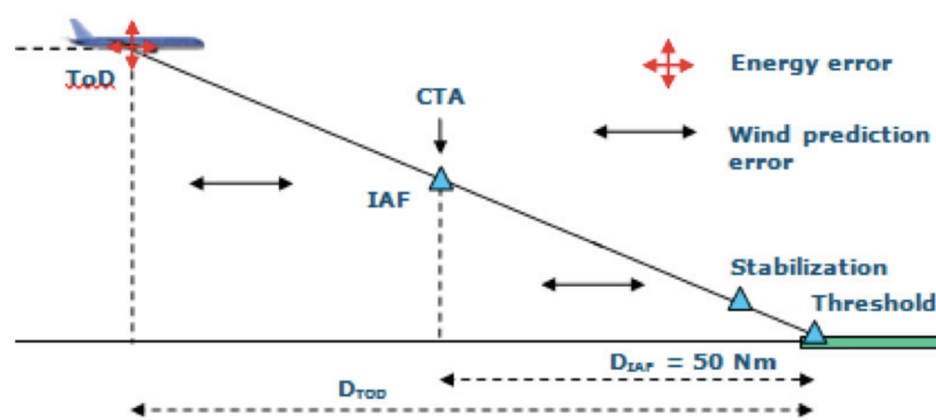
## Guidance function

- Speed-on-elevator control (instead of conventional VNAV-path)
- Energy and Time deviations monitored
- If predefined boundaries exceeded a new re-plan is commanded (strategic guidance)
- Tactical guidance also possible to nullify time deviation errors

Re-planning command

RTA update

Air Traffic Control (ATC)



# TEMO trajectory optimisation

Minimise $$J = \int_{t_{TOD}}^{t_f} FF(t) + \beta(t)\,\mathrm{d}t$$

States: $v_a, s, h, m$

Controls: $N1, \beta, \xi$

Input data

Subject to:

$$\dot{v}_a = \frac{T - D}{m} - g \sin \gamma_a - \dot{W}_v$$

$$\dot{s} = \sqrt{{v_a}^2 \cos^2 \gamma_a - W_x^2} + W_s$$

$$\dot{h} = v_a \sin \gamma_a$$

$$\dot{m} = -FF$$

$$FF(v_a, h, N1)$$
$$T(v_a, h, N1)$$
$$D(v_a, h, \gamma_a, \beta, \xi)$$

$$W_s(\chi_g, W_n, W_e)$$
$$W_x(\chi_g, W_n, W_e)$$

$$\dot{W}_v(v_a, \gamma_a, \chi_g, \dot{W}_n, \dot{W}_e)$$

and…

# TEMO trajectory optimisation

| Phase | Name | Initial/final conditions | Configuration | Optimization Constraints |
|---|---|---|---|---|
| 1 | Cruise | $h_p(t_0) = 30,000\,\text{ft}$<br>$s(t_0) = s_0$<br>$t_f \geq t_0 + \Delta t_{ATC}$ | Clean<br>Gear UP | $\beta(t) = 0$<br>$\dot{M}(t) = 0$<br>$M_{min} \leq M(t) \leq MMO$<br>$h_p(t) = 30,000\,\text{ft}$ |
| 2 | Mach descent | | Clean<br>Gear UP | $\dot{M}(t) = 0$<br>$M_{min} \leq M(t) \leq MMO$ |
| 3 | CAS descent | | Clean<br>Gear UP | $\dot{v}_{CAS}(t) = 0$<br>$v_{CAS_{min}} \leq v_{CAS}(t) \leq VMO$ |
| 4 | Fast Deceleration | $h(t_f) \geq 8,000\,\text{ft}$<br>$215\,\text{kt} \leq v_{CAS}(t_f) \leq 250\,\text{kt}$ | Clean<br>Gear UP | $\ddot{v}_{CAS}(t) = 0$<br>$-1.6\,\text{kt/s} \leq \dot{v}_{CAS}(t) \leq +0.5\,\text{kt/s}$ |
| 5 | CAS approach | $s(t_0) = s_{TOLKO}$<br>$t_0 = RTA_{TOLKO}$ | Clean<br>Gear UP | $\dot{v}_{CAS}(t) = 0$<br>$215\,\text{kt} \leq v_{CAS}(t) \leq 250\,\text{kt}$ |
| 6 | Approach Deceleration 1 | $h_p(t_f) \geq 3,500\,\text{ft}$<br>$v_{CAS_{min}} \leq v_{CAS}(t_f) \leq 220\,\text{kt}$ | Clean<br>Gear UP | $\ddot{v}_{CAS}(t) = 0$<br>$-1.0\,\text{kt/s} \leq \dot{v}_{CAS}(t) \leq -0.3\,\text{kt/s}$ |
| 7 | Approach Deceleration 2 | $s(t_0) = s_{EH740}$<br>$v_{CAS_{min}} \leq v_{CAS}(t_f) \leq v_{CAS_{F1max}}$ | Clean<br>Gear UP | $\ddot{v}_{CAS}(t) = 0$<br>$-0.9\,\text{kt/s} \leq \dot{v}_{CAS}(t) \leq 0.2\,\text{kt/s}$ |
| 8 | Approach Deceleration 3 | $h_p(t_f) = 2,000\,\text{ft}$ | Flaps F1 | $\ddot{v}_{CAS}(t) = 0$ |
| 9 | CAS on GS | | | |
| 10 | Deceleration on GS | | | |
| 11 | GS stabilized | | | |

Original Optimal control problem discretised by **collocation** methods and solved with Non Linear Programming (**NLP**)

# TEMO model improvements

- **Inclusion of realistic wind fields and non-standard atmosphere**
  - Air pressure, temperature and horizontal wind dependency on **altitude** and **geographic location**
  - Data fitted to B-spline functions
  - Data source: standard weather GRIB files

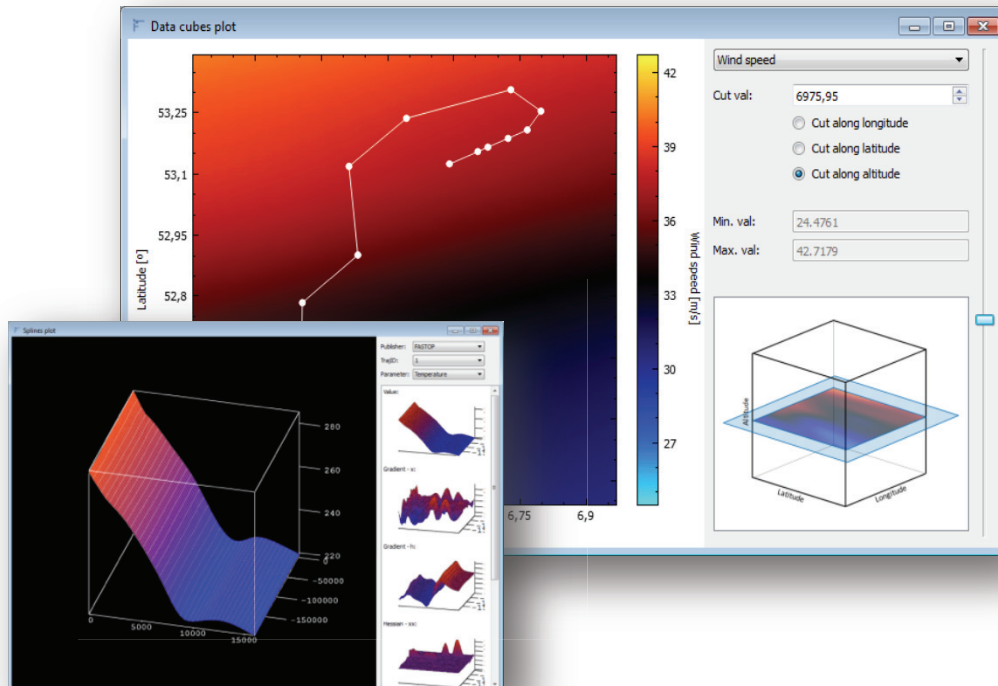
$$W_n(h,s) \quad W_e(h,s)$$

$$\tau(h,s) \quad p(h,s)$$

$$W_s(\chi_g, W_n, W_e)$$

$$W_x(\chi_g, W_n, W_e)$$

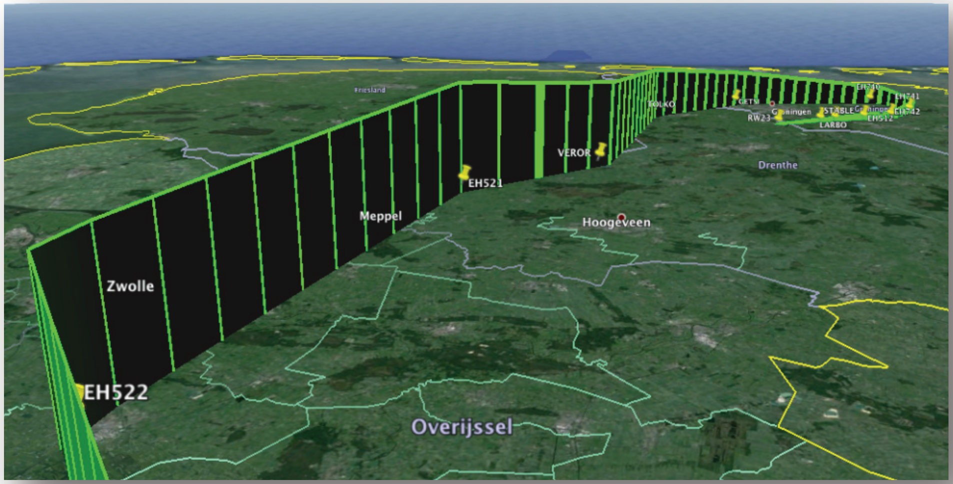
$$\dot{W}_v(v_a, \gamma_a, \chi_g, \dot{W}_n, \dot{W}_e)$$



# TEMO model improvements

- **Consideration of curved approaches**
  - The arrival procedure follows fixed RNAV/RNP routes
  - Effect of bank angle on aerodynamic drag modeled
  - Effect of wind, as aircraft changes heading, modeled

- **Re-implementation in C++**
  - Interfacing with GAMS and CONOPT (as NLP)




RNAV: area navigation - RNP: Required Navigation Performance – NLP: Non-Linear Programming

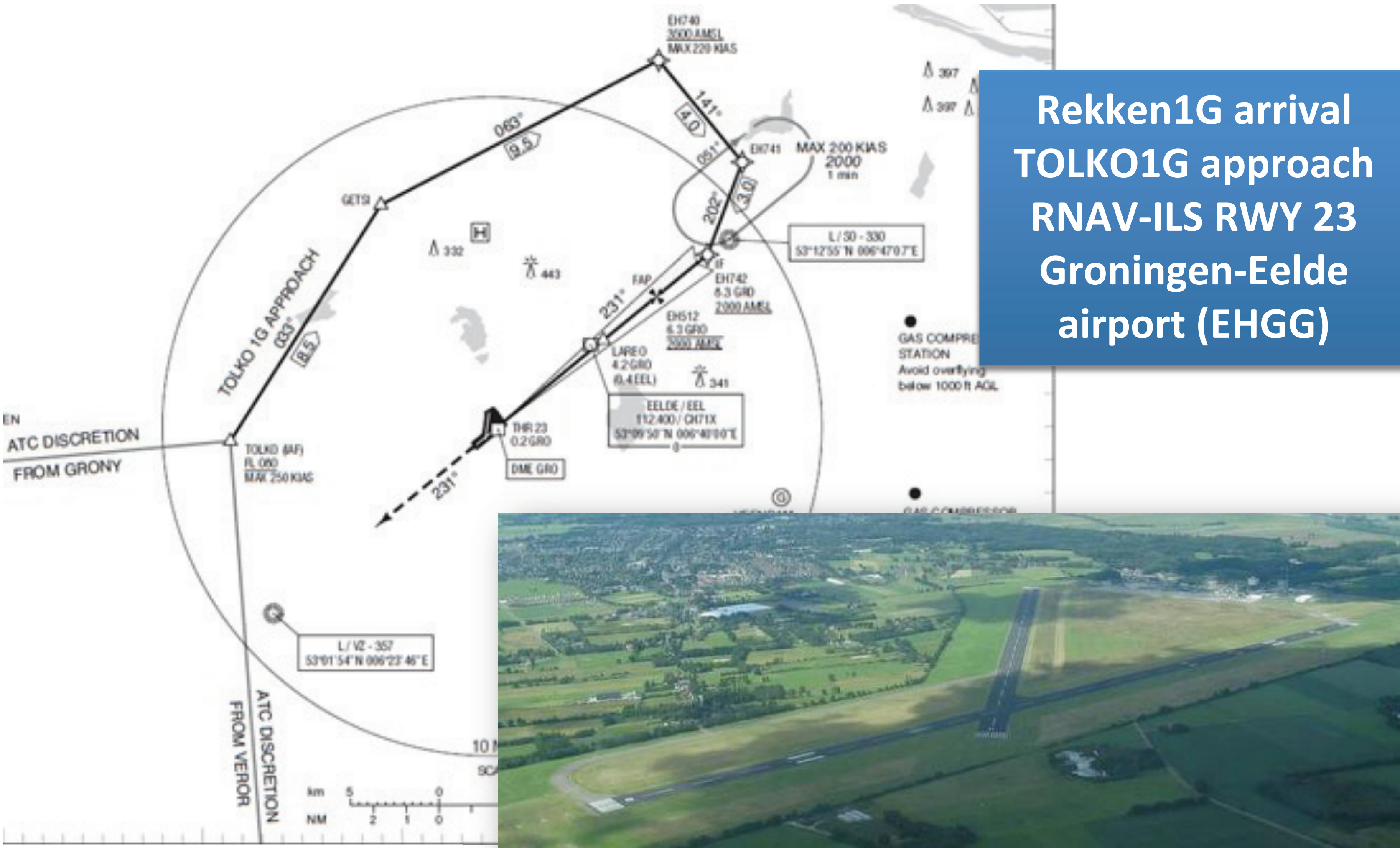
# Experiment setup

- **Human-in-the-loop experiments with realistic routing scenarios**

3 full days in July 2014 at NLR's GRACE full flight simulator


# Experiment setup

- **Human-in-the-loop experiments** with realistic routing scenarios




Rekken1G arrival
TOLKO1G approach
RNAV-ILS RWY 23
Groningen-Eelde
airport (EHGG)

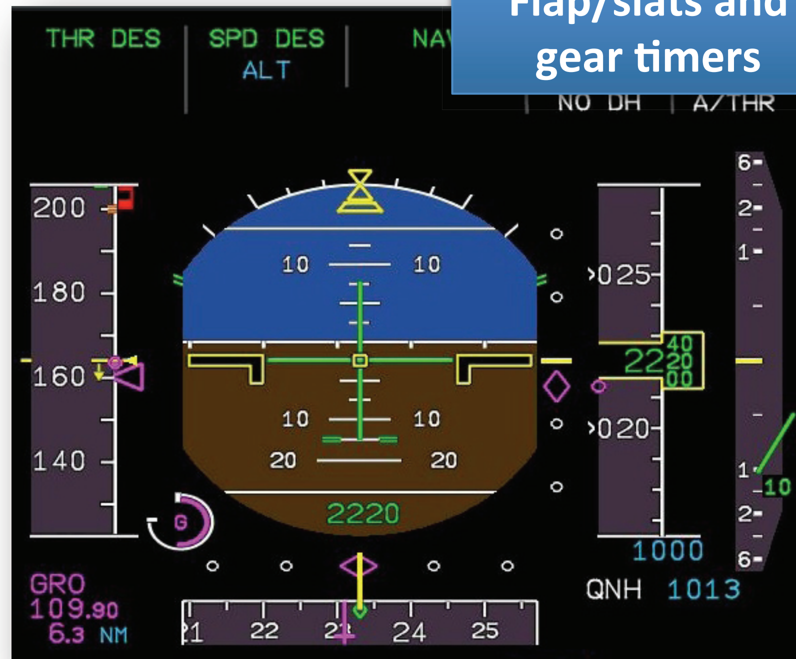
# Experiment setup

- 2 pilot crew
- Cessna Citation C550 model but *Airbus-like* cockpit
- Auto speed-brake functionality capable to follow continuous speed-brake functions
- Simulation starting at cruise (FL300/M0.6)
- RTA at the IAF and at the runway threshold
- ASAS-IM operations (for some runs)
- Data-link clearances and RTAs


IM: Interval Management
ASAS: Airborne Separation Assurance System

# Experiment setup

## Specific Human Machine Interface features

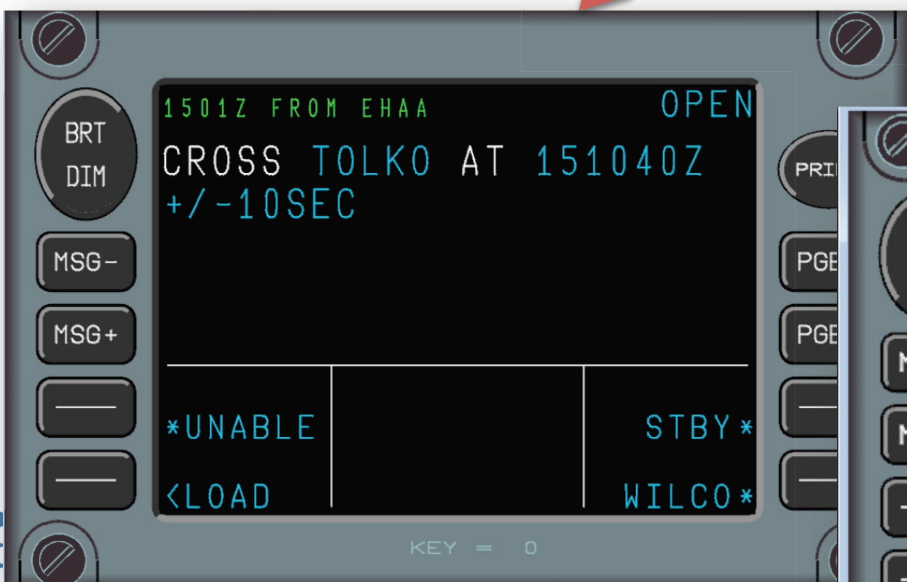




**Flap/slats and gear timers**


**Cues for flap/slats and gear changes**
**Cues for throttle/speedbrake segments**

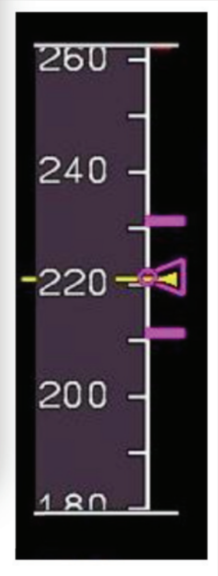
# Experiment setup

| | IAF metering | Runway metering | Guidance |
|---|---|---|---|
| Scenario 1 | RTA | RTA | Strategic |
| Scenario 2 | RTA | IM-Achieve | Strategic |
| Scenario 3 | RTA | IM-Achieve | Hybrid |




# Experiment setup

| | IAF metering | Runway metering | Guidance |
|---|---|---|---|
| Scenario 1 | RTA | RTA | Strategic |
| Scenario 2 | RTA | IM-Achieve | Strategic |
| Scenario 3 | RTA | IM-Achieve | Hybrid |


Re-plan if time or energy deviations exceed max. bounds

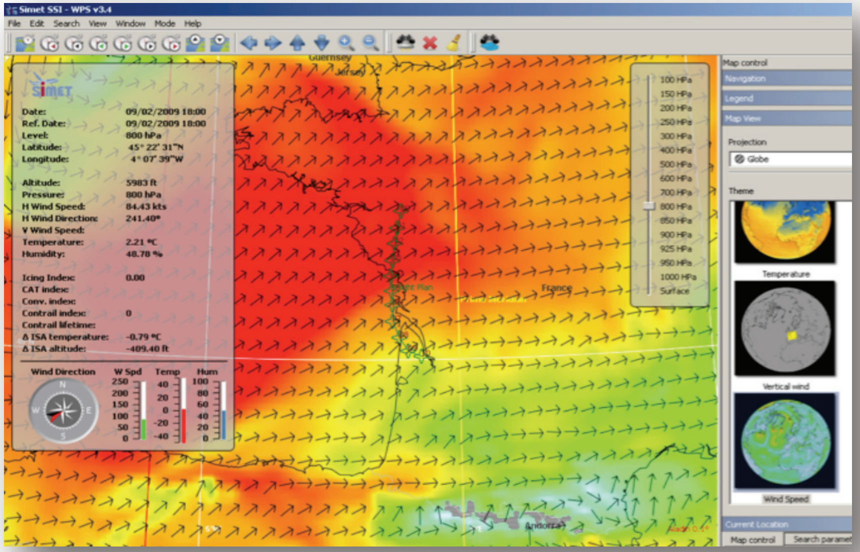
Re-plan if energy exceed max. bounds + tactical controller on speed to nullify time deviations

# Experiment setup

| | IAF metering | Runway metering | Guidance |
|---|---|---|---|
| Scenario 1 | RTA | RTA | Strategic |
| Scenario 2 | RTA | IM-Achieve | Strategic |
| Scenario 3 | RTA | IM-Achieve | Hybrid |

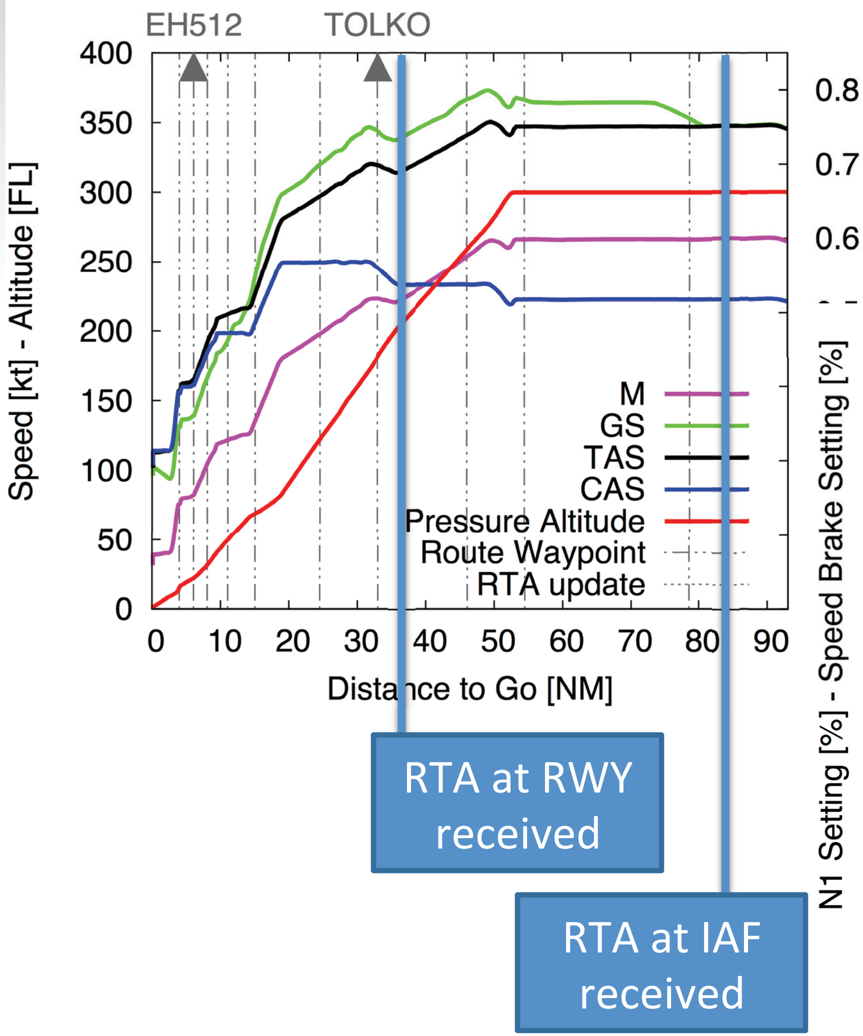
For each scenario 4 Runs:

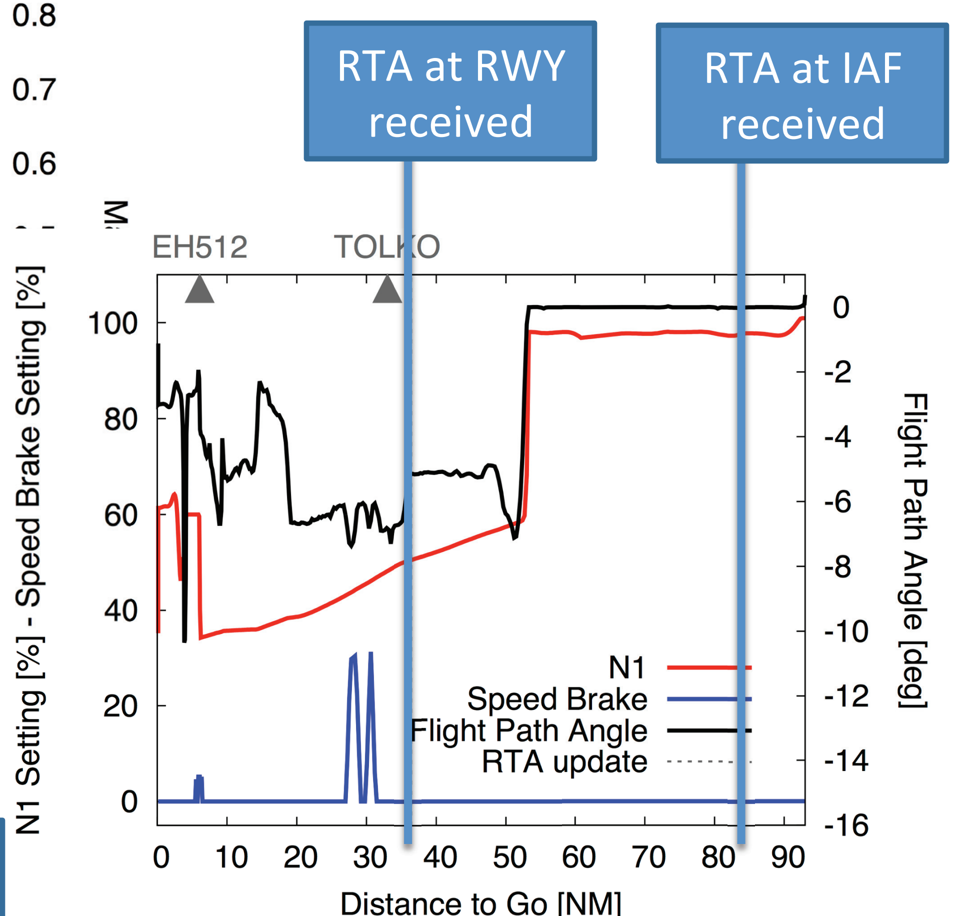
- Run-1: No wind forecast errors
- Run-2: Wind error (3kt, 2º)
- Run-3: Wind error (6kt, 4º)
- Run-4: Wind error (9kt, 6º)



# Experiment results

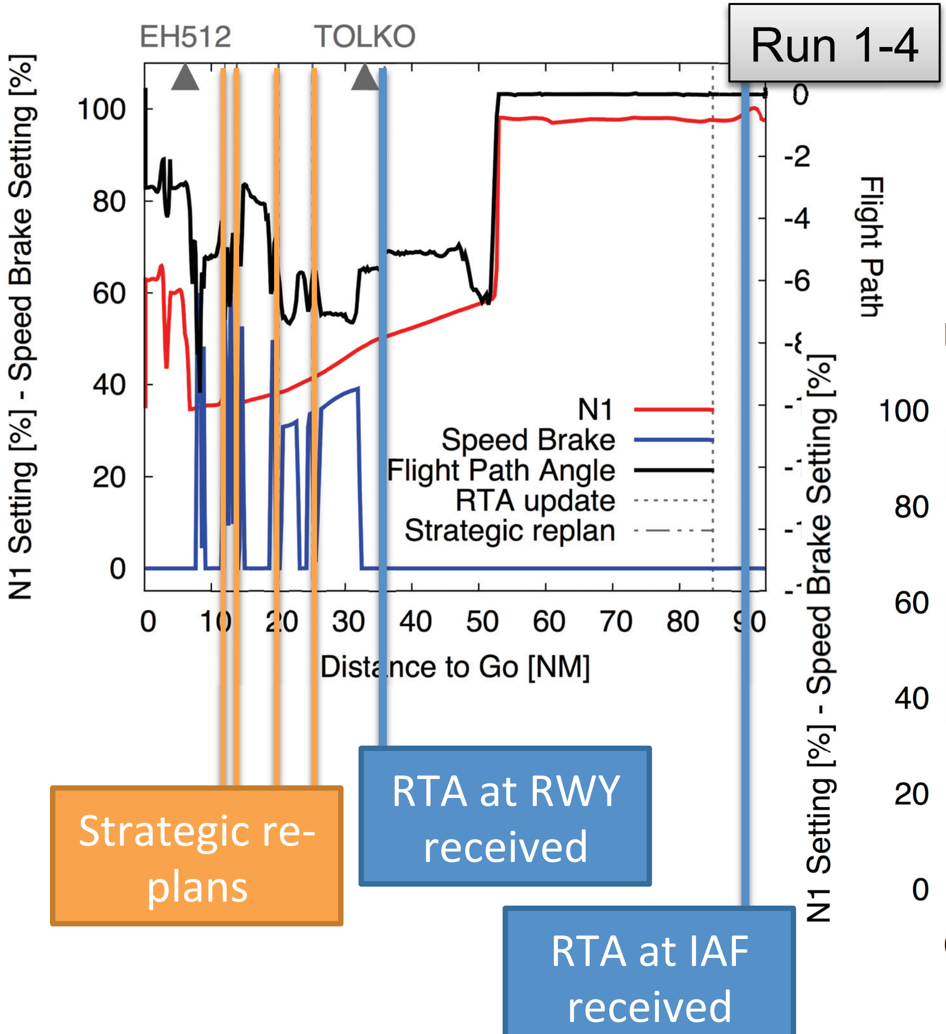
## Trajectories for Run 1-1

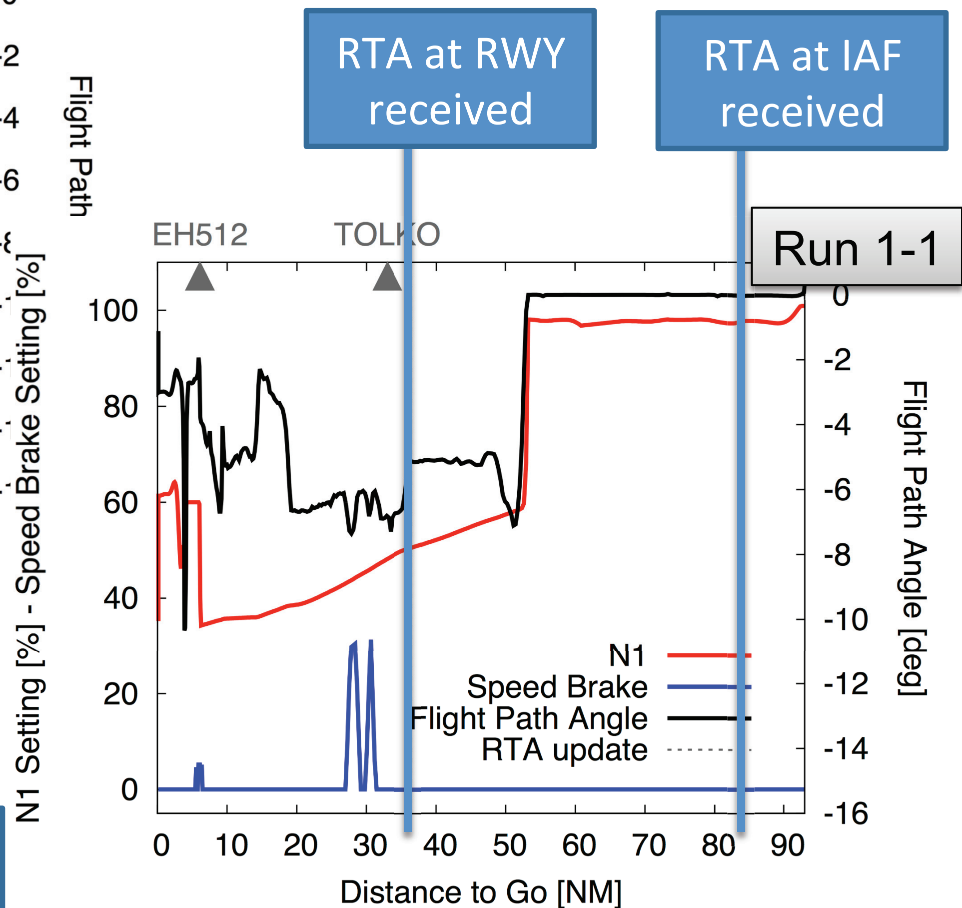


# Experiment results

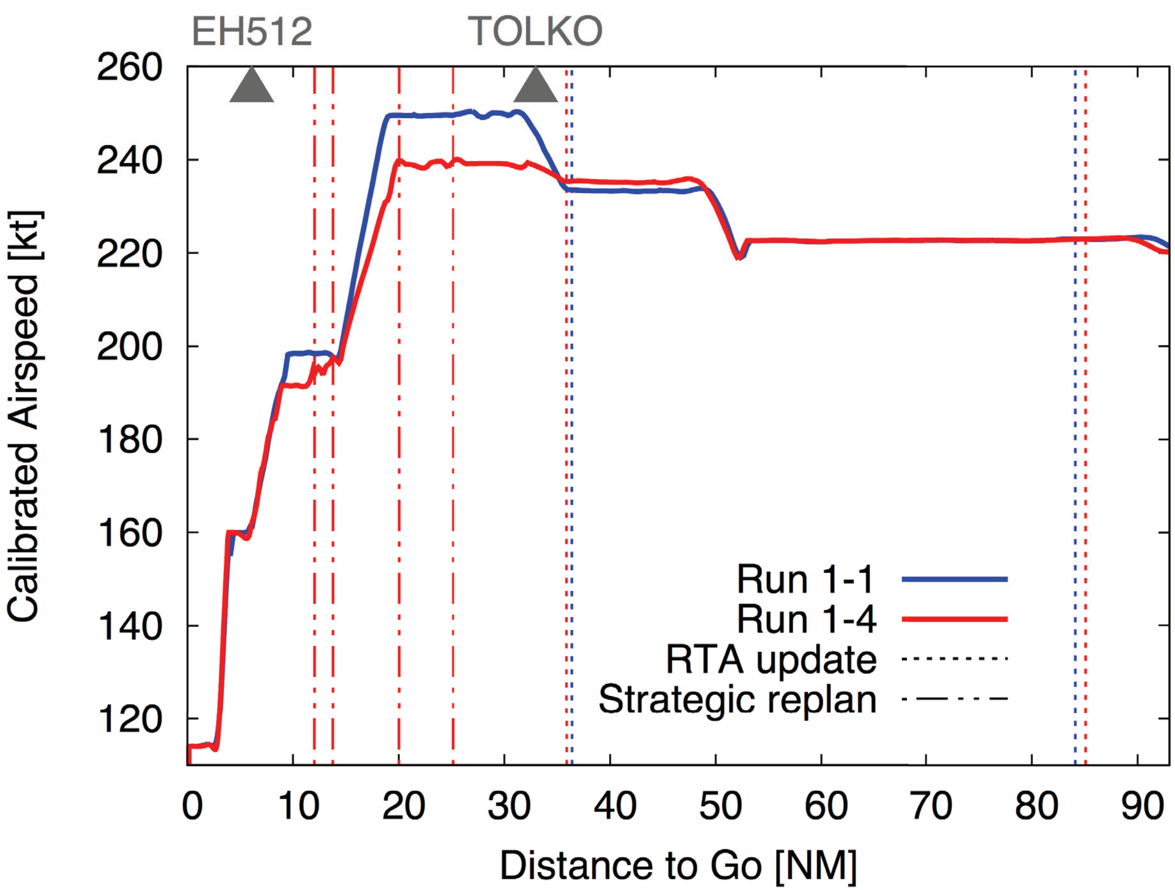
## Controls for Runs 1-1 and 1-4



# Experiment results

## CAS profiles for for Runs 1-1 and 1-4

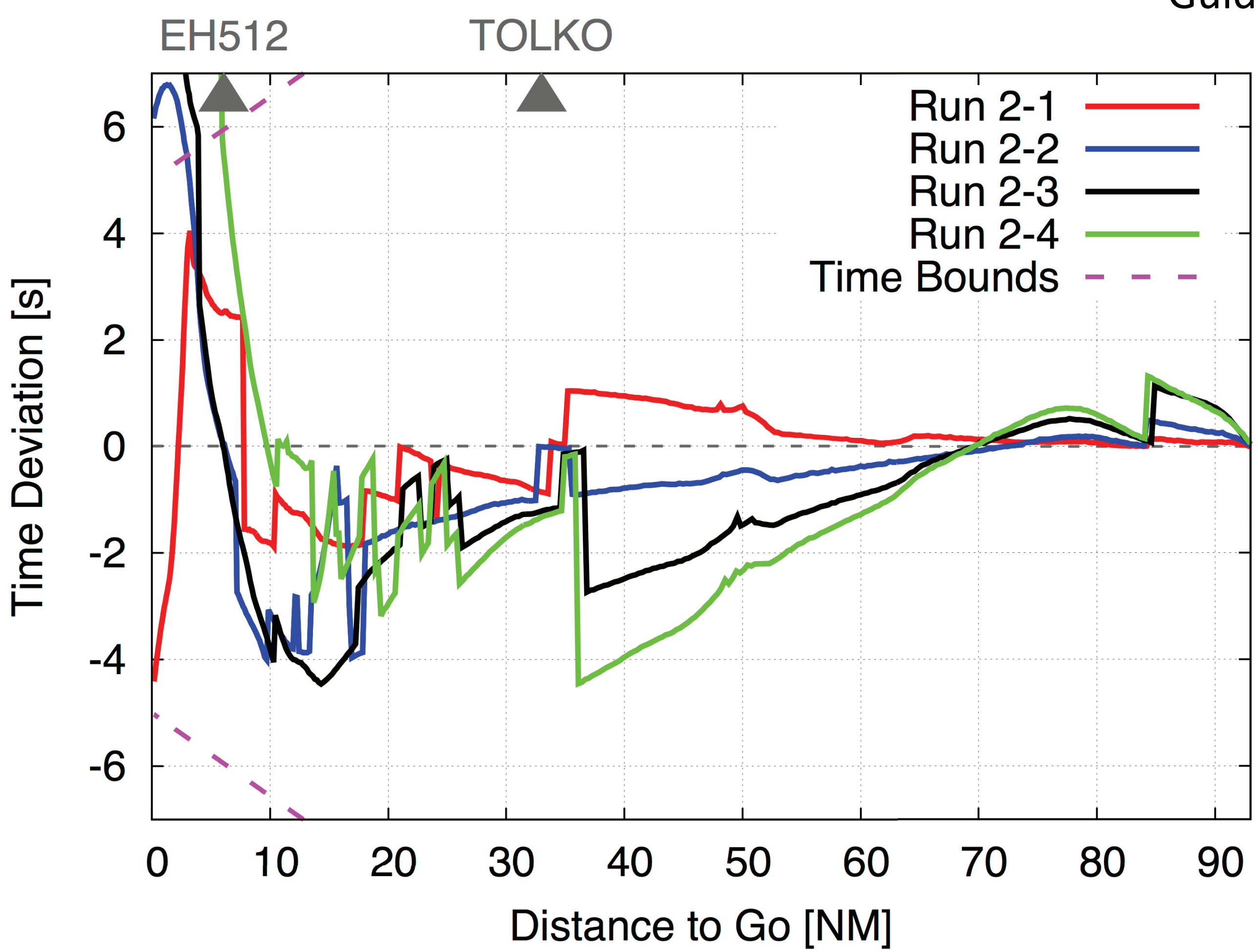


# Experiment results

## Time deviations for Scenario 2

RWY metering: IM-achieve

Guidance: Strategic



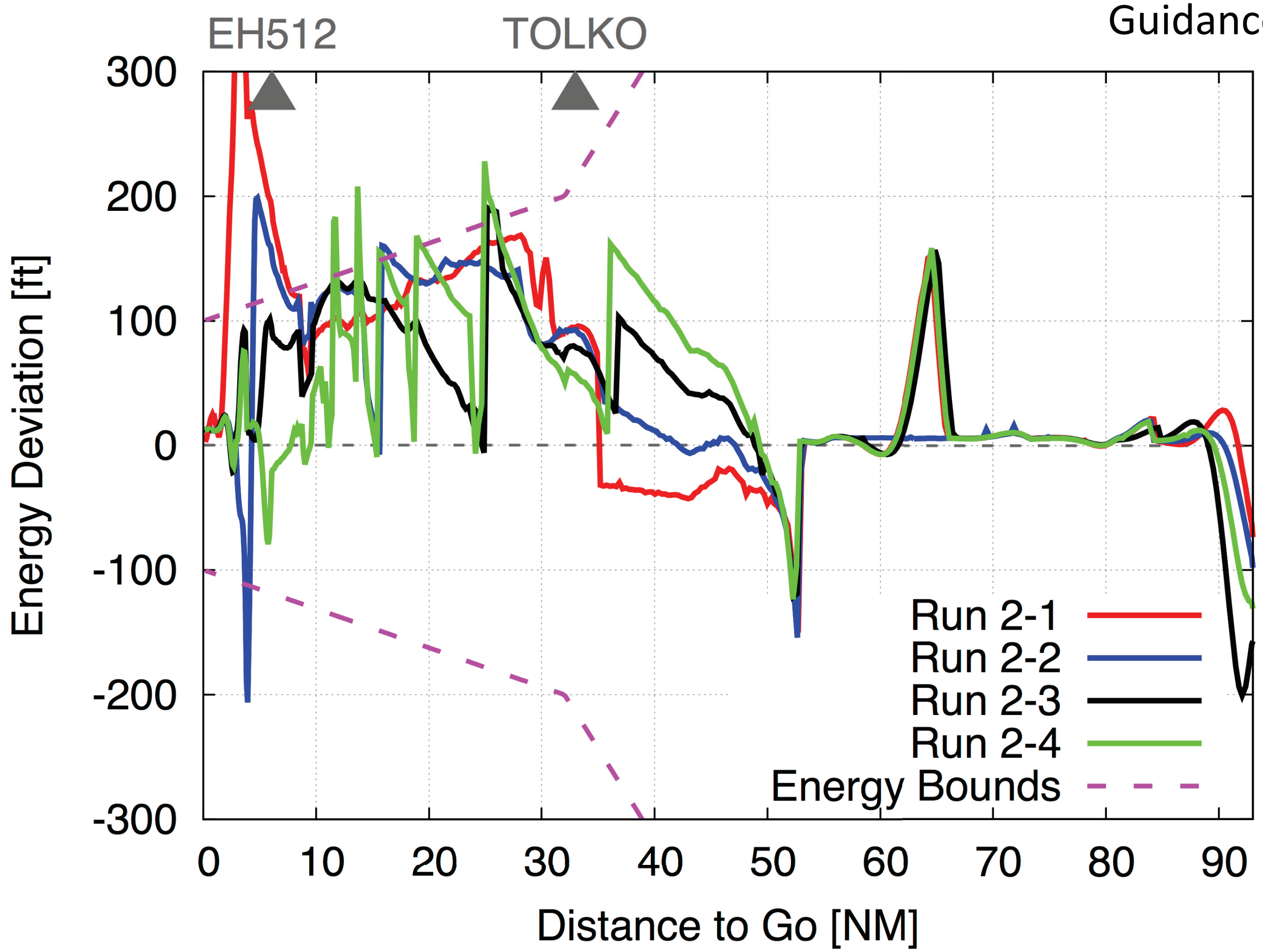

Large time deviations after APPR mode engaged (which disables TEMO logic)

# Experiment results

## Energy deviations for Scenario 2

RWY metering: IM-achieve

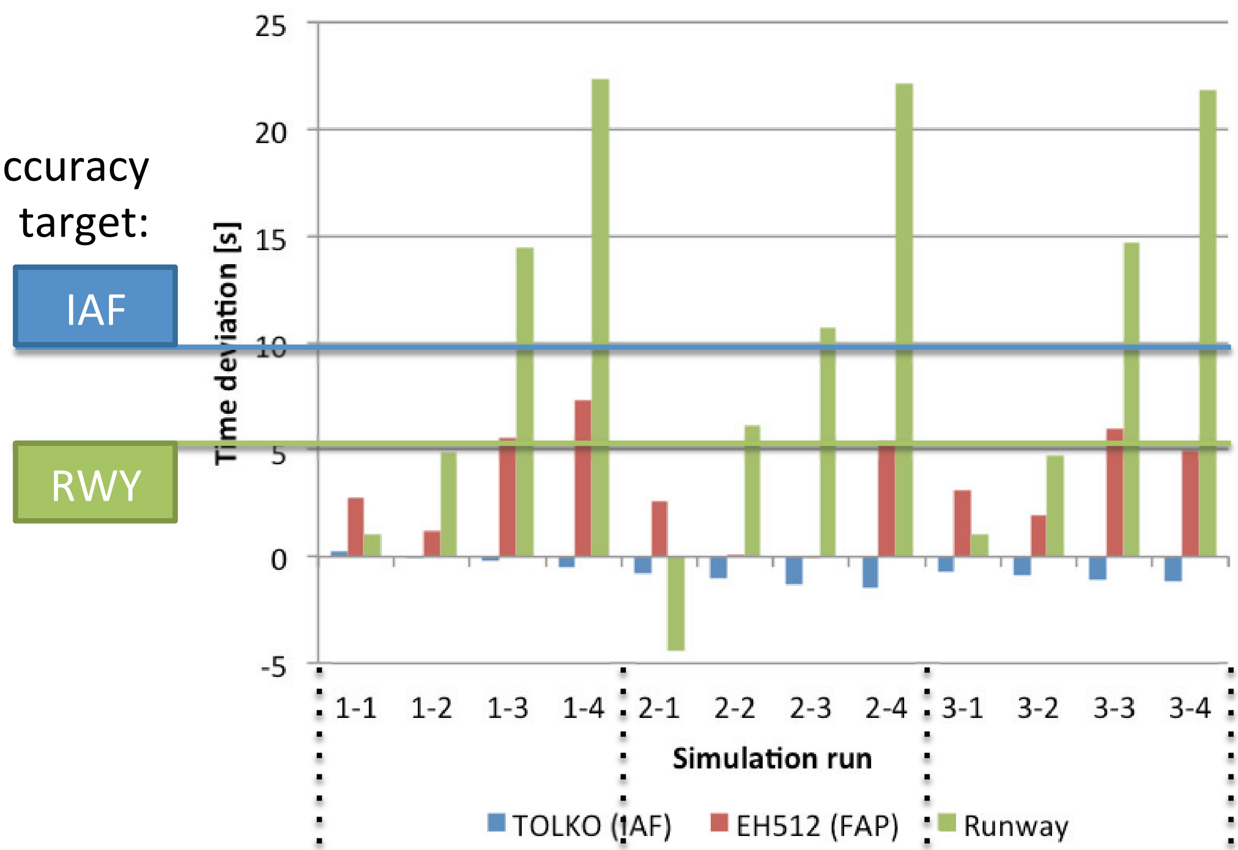
Guidance: Strategic



# Experiment results

## Time deviations

Time accuracy target:




| | | | |
|---|---|---|---|
| RWY metering: | RTA | IM-achieve | IM-achieve |
| Guidance: | Strategic | Strategic | Hybrid |

Time accuracy at IAF well below time objectives of +/-10s

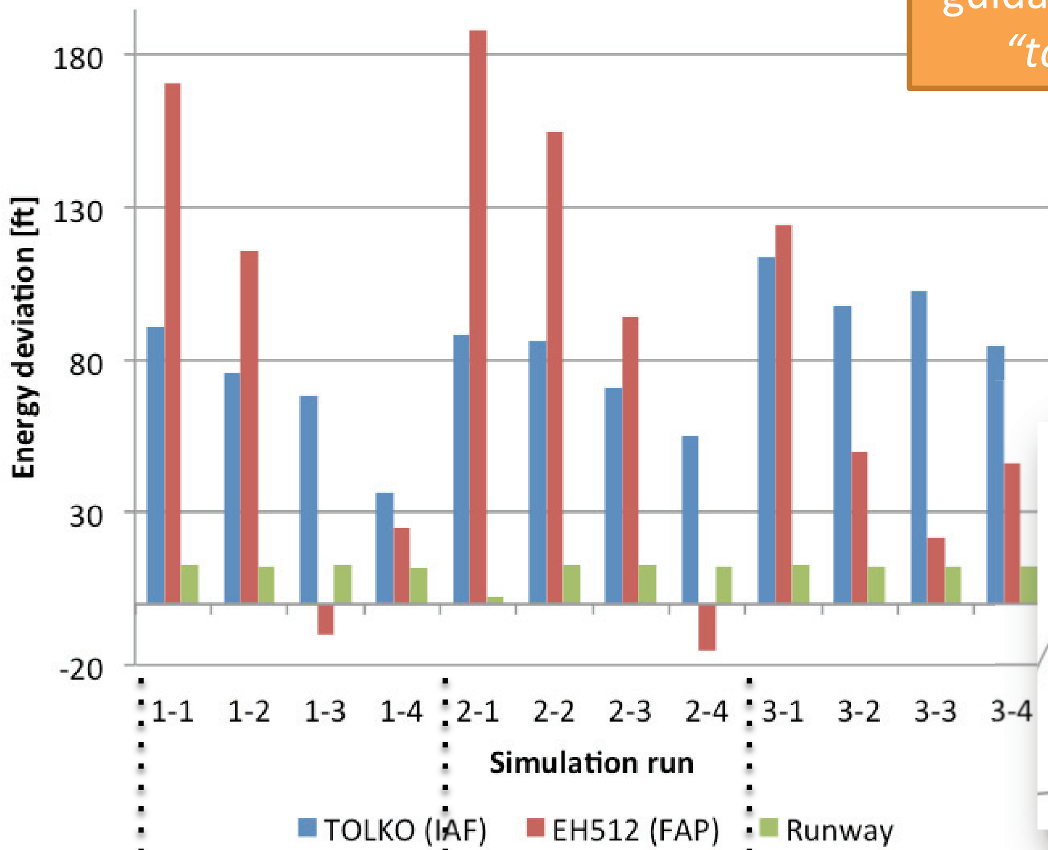
Large time deviations after APPR mode engaged (which disables TEMO logic)
Engine dynamics not modelled

At FAP time accuracy objectives (+/-5s) )met for almost all Runs

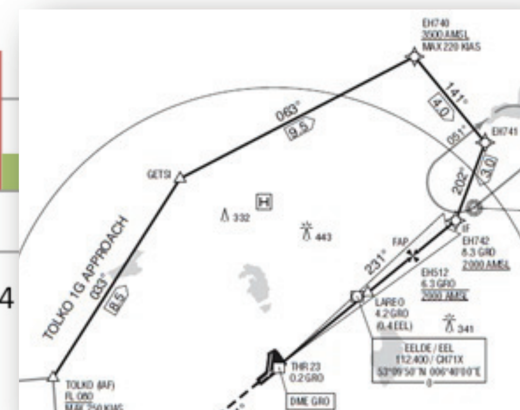
# Experiment results

## Energy deviations

Due to modelling and guidance errors aircraft was *"too high" (in energy)*




Route turn on final compensates wind forecast errors




| | | | |
|---|---|---|---|
| RWY metering: | RTA | IM-achieve | IM-achieve |
| Guidance: | Strategic | Strategic | Hybrid |

# Conclusions

- Time and Energy managed operations (TEMO) as a solution for environmentally friendly procedures in high-density TMAs
- Importance of wind and real atmosphere accurate modeling to achieve very demanding time accuracies, specially at lower altitudes and speeds.
- Some improvements still needed: avoiding to intercept ILS glideslope from above, improve estimation of initial position, model engine dynamics in final approach, …
- Flight trials with Cessna C550 scheduled in October 2015.

# Thank you!
# Děkuji!

# Any Questions?

CLEANSKY

FASTOP

Concorde

**FASTOP and CONCORDE projects** were partially funded from the European Union's 7th Framework Programe through the **Clean Sky** Joint Technology Initiative under Grant Agreements no. **CS-GA-2013-323495** and **CS-GA-2013-620130**, respectively.

# Backup Slides

CLEANSKY FASTOP Concorde

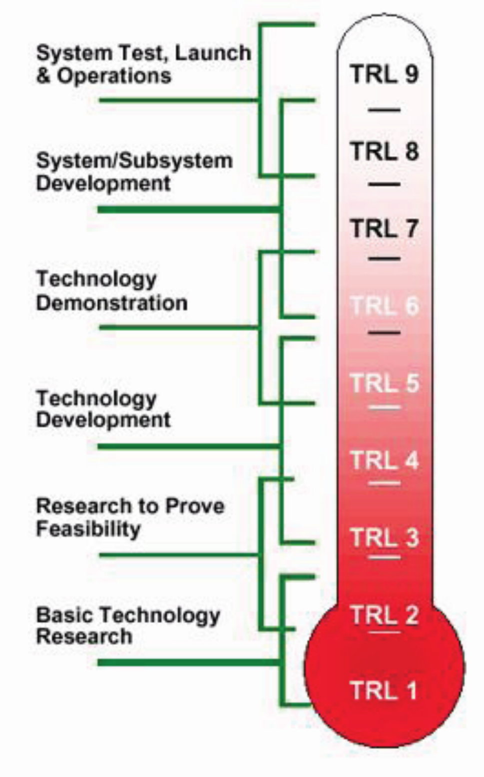
**FASTOP and CONCORDE projects** were partially funded from the European Union's 7th Framework Programe through the **Clean Sky** Joint Technology Initiative under Grant Agreements no. **CS-GA-2013-323495** and **CS-GA-2013-620130**, respectively.

# TEMO

- TEMO achieved the technology readiness level 4 (TRL-4) in 2012. Simulation batch studies were carried out to proof the concept.
- FASTOP project enhanced the current version of the TEMO planning in order to test it in more realistic environments (aiming at the TRL-5 gate)
- TEMO achieved TRL-5 in Dec. 2014 with the support of CONCORDE project

  → 2 simulation experiments
  (NLR's GRACE and DLR's GECO Simulators)

- Within the CONCORDE project, 1 flight trial campaign is planned in Oct 2015 with a Cessna C550 aiming to achieve the TRL5+ gate.




*TRL-5: "Technology component validation in relevant environment"*

## FASTOP and Concorde projects

CLEANSKY

NLR

Topic Manager

FASTOP (2012-2013)

gtd

Project Leader

UNIVERSITAT POLITÈCNICA DE CATALUNYA

ascamm centro tecnológico

CLEANSKY

NLR

DLR

Topic Managers

Concorde (2014-2015)

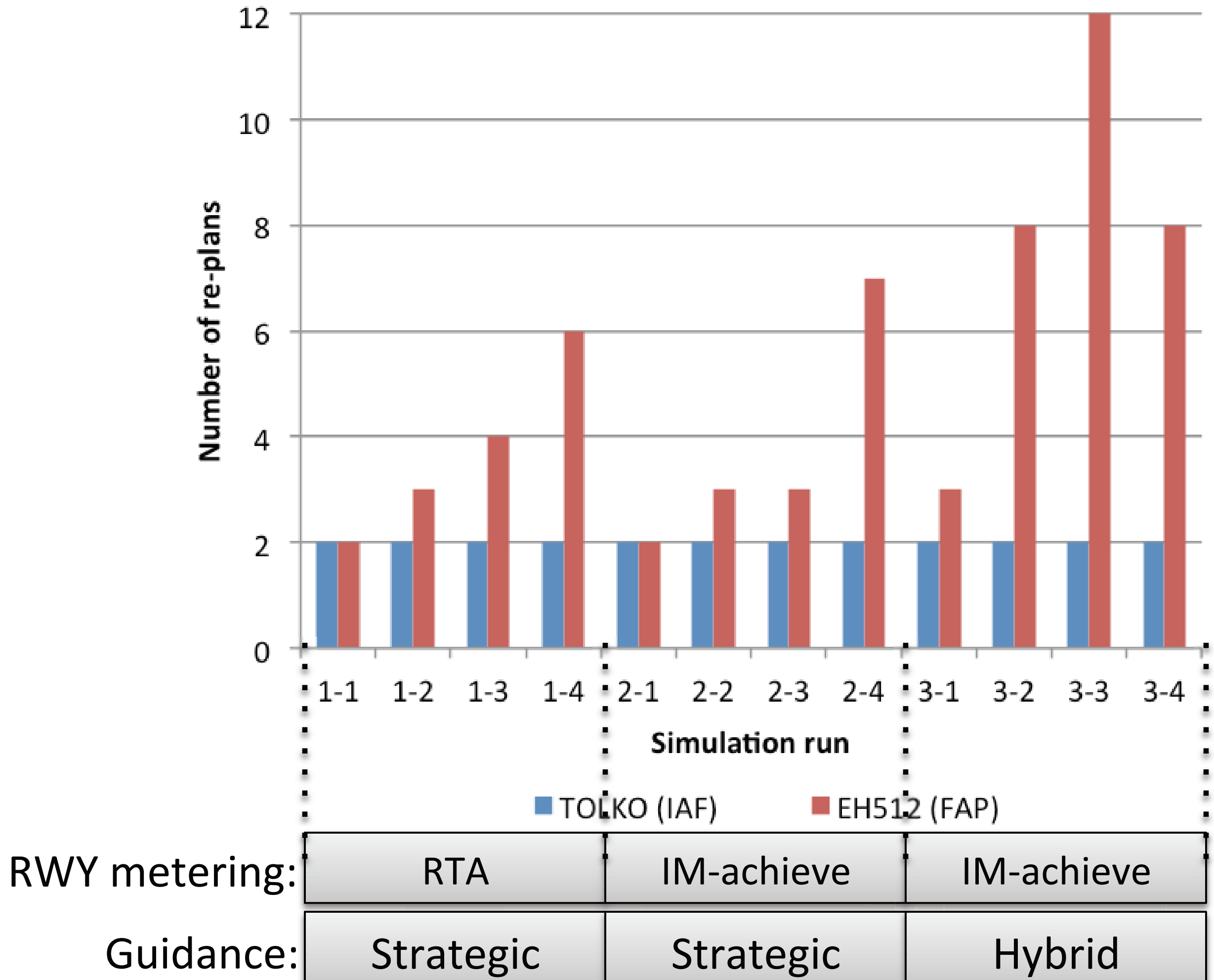
Project Leader

PildoLabs

UNIVERSITAT POLITÈCNICA DE CATALUNYA

# Experiment results

## Number of strategic re-plans




Wind forecast errors more important at lower TAS

Smaller energy/time max. deviations when approaching the RWY