Aircraft trajectory optimization

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The problem

Aircraft simulation models

Performance modeling

Methods for solution

Interactive use and remote computing

Flight testing

Future developments

Aircraft simulation models

Exist for everything: Structures, Aerodynamics, Controls, Subsystems

Different models for different purposes

Ordinary and partial differential equations

Sometimes also with integral terms (memory)

Some are interactive others run in batch

Flight simulator

- Rigid body six-degrees of freedom (position and orientation)
- Aerodynamic force modeling is (very) complex
- Flight testing and wind tunnels are the main sources
- System of nonlinear ODEs: $f(\dot{x}, x, u) = 0$
- 12 primary state variables in x
- Total number for JAS-39 Gripen is about 2500
- Stick, pedals, throttle and many more define u
- Simulators typically run at 60-240 Hz

Trajectory optimization

Compute optimal trajectory for minimum time, minium fuel etc

Performance data from Saab

Aircraft equations of motion are discretized

Numerical optimization finds optimal control for a given mission

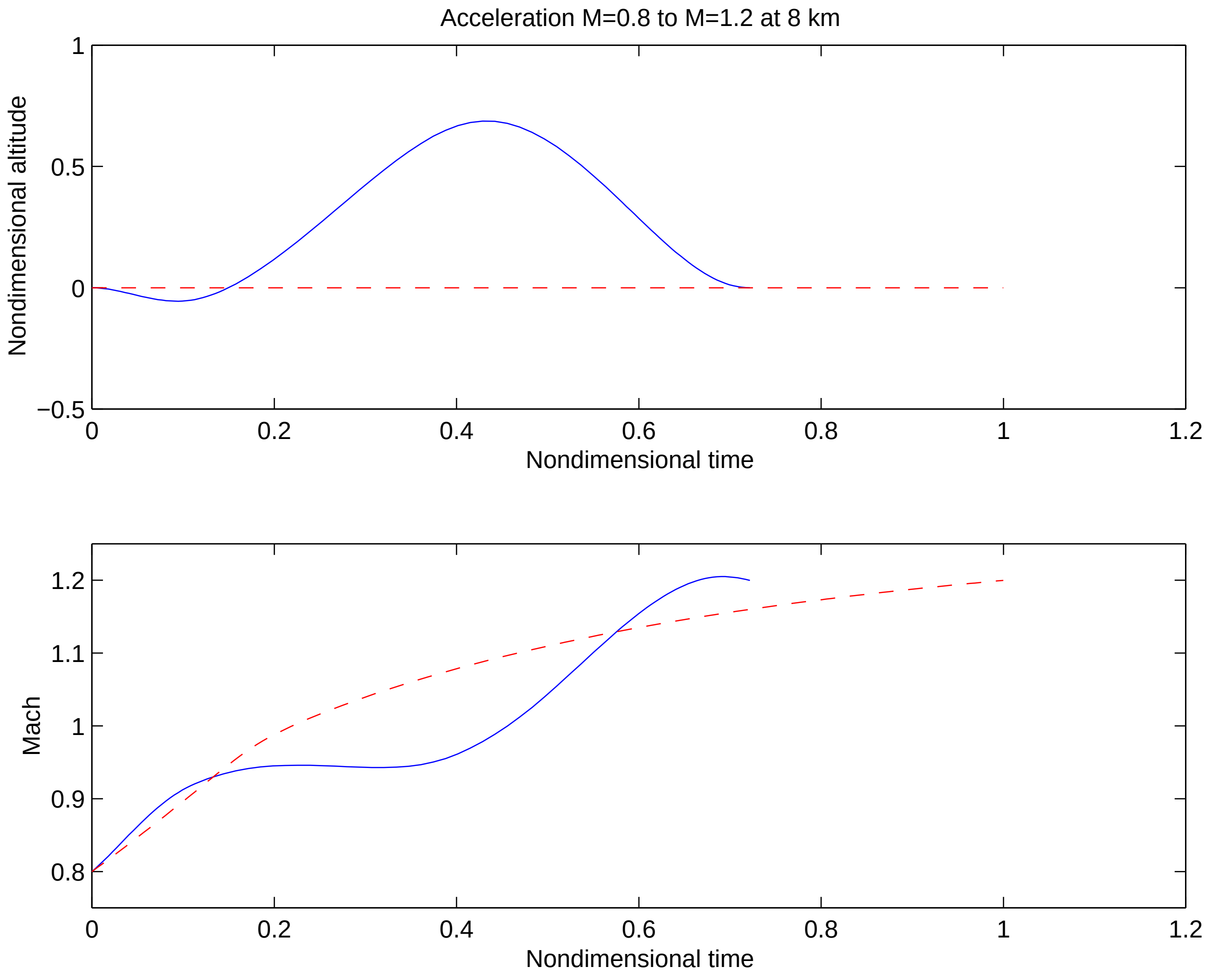
Optimal acceleration for J35 Draken

Minimize time

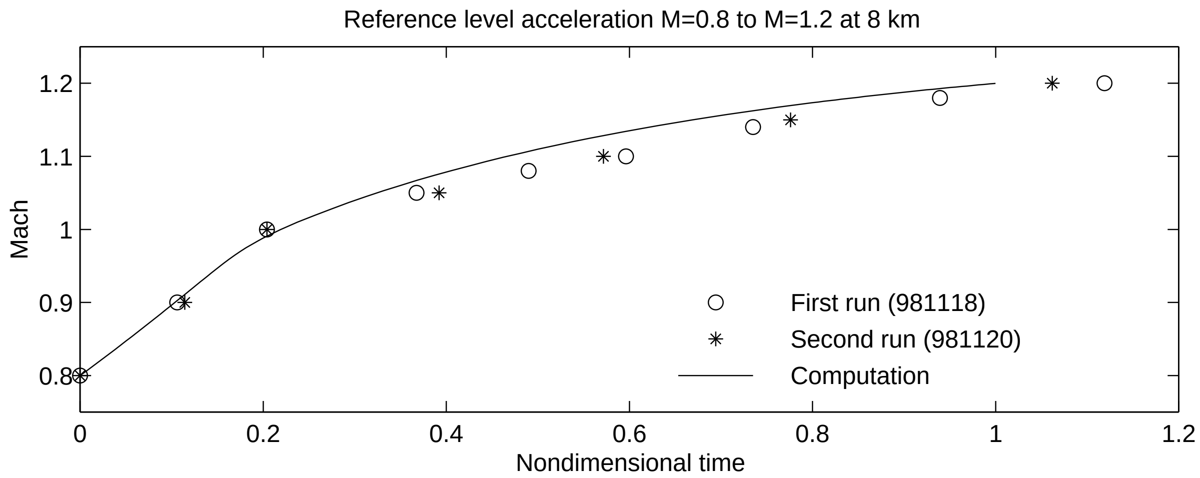
Initial condition: level flight, Mach 0.8, altitude 8 km

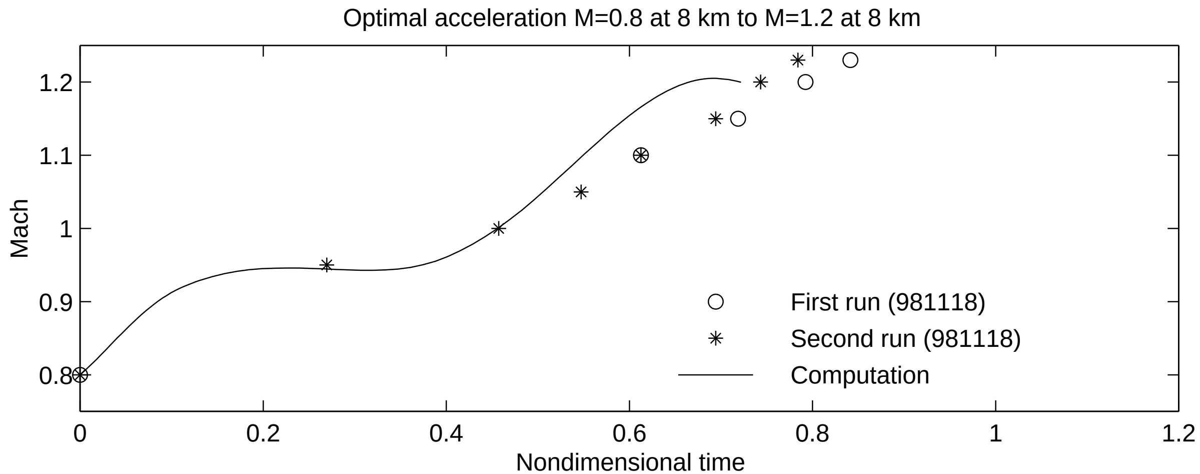
Final condition: level flight, Mach 1.2, altitude 8 km

Numerical results

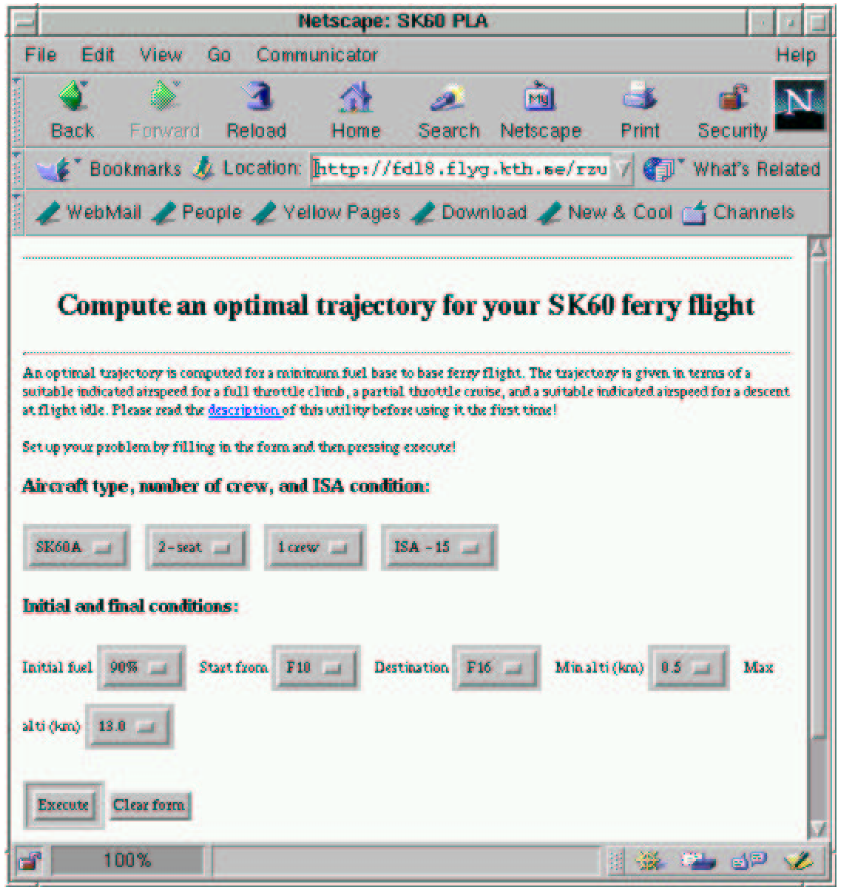


Flight test, Dan Eriksson (2.div F10)





Web version for SK60



- Familiar user interface
- No manuals
- No distribution/installation
- Easy to upgrade and modify
- Low cost, Linux PC
- Efficient, solution in 5-10 s
- Graphics and listing presented to the user

Optimal trajectories for SK60 with your WAP-phone

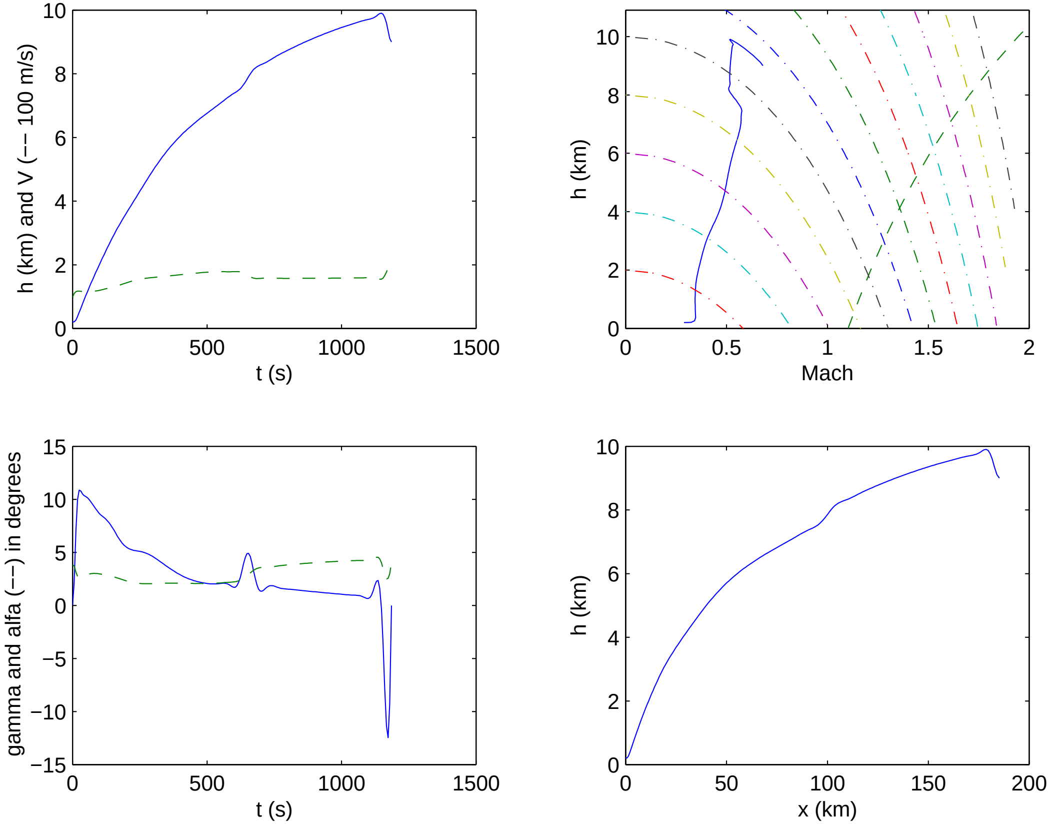
- WAP compatible cellular phone
- Input data is sent to a server at KTH
- The trajectory is computed
- The nonlinear optimization problem is solved
- Time 5-10 s
- The pilot instruction is shown on the phone display

Field testing with the Swedish Air Force

Flight testing

Minimum time to climb
Minimum fuel to climb
Minimum time base to base
Minimum fuel base to base
Evaluation using GPS

Minimum time to climb strategy



Initial condition

Fuel 90 %

Altitude 0.2 km

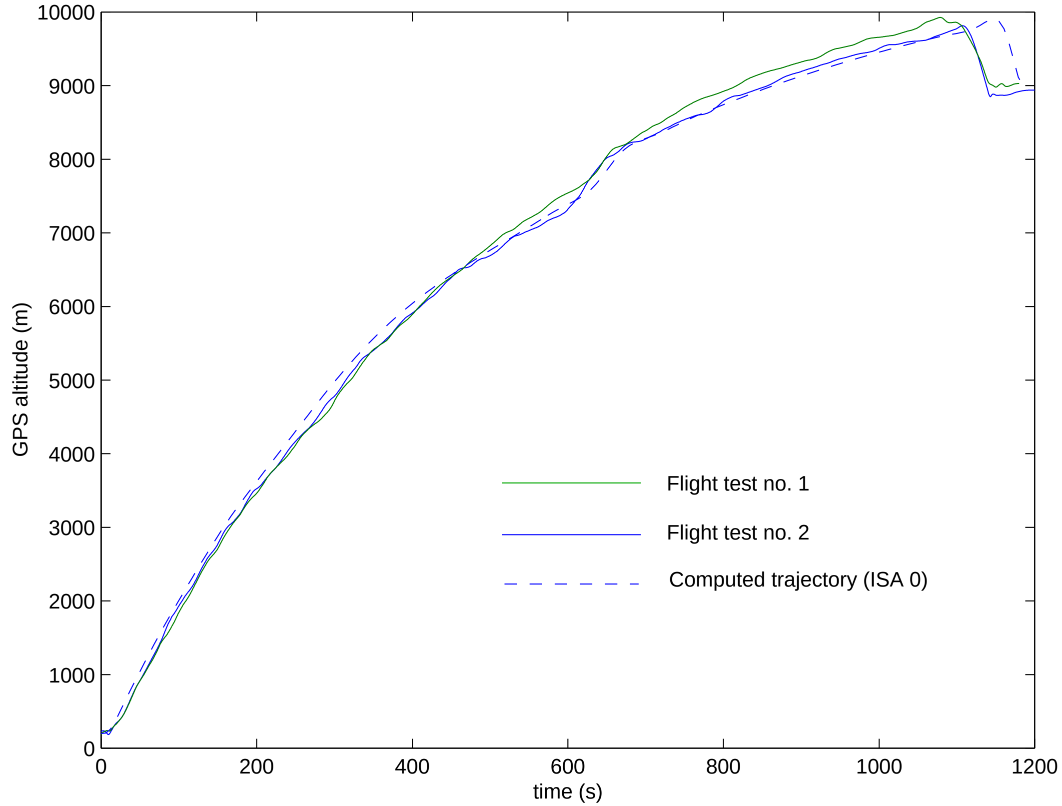
Indicated airspeed 350 km/h

Final condition

Altitude 9 km

Mach 0.68

Minimum time to climb



Initial condition

Altitude 0.2 km
Indicated airspeed 350 km/h

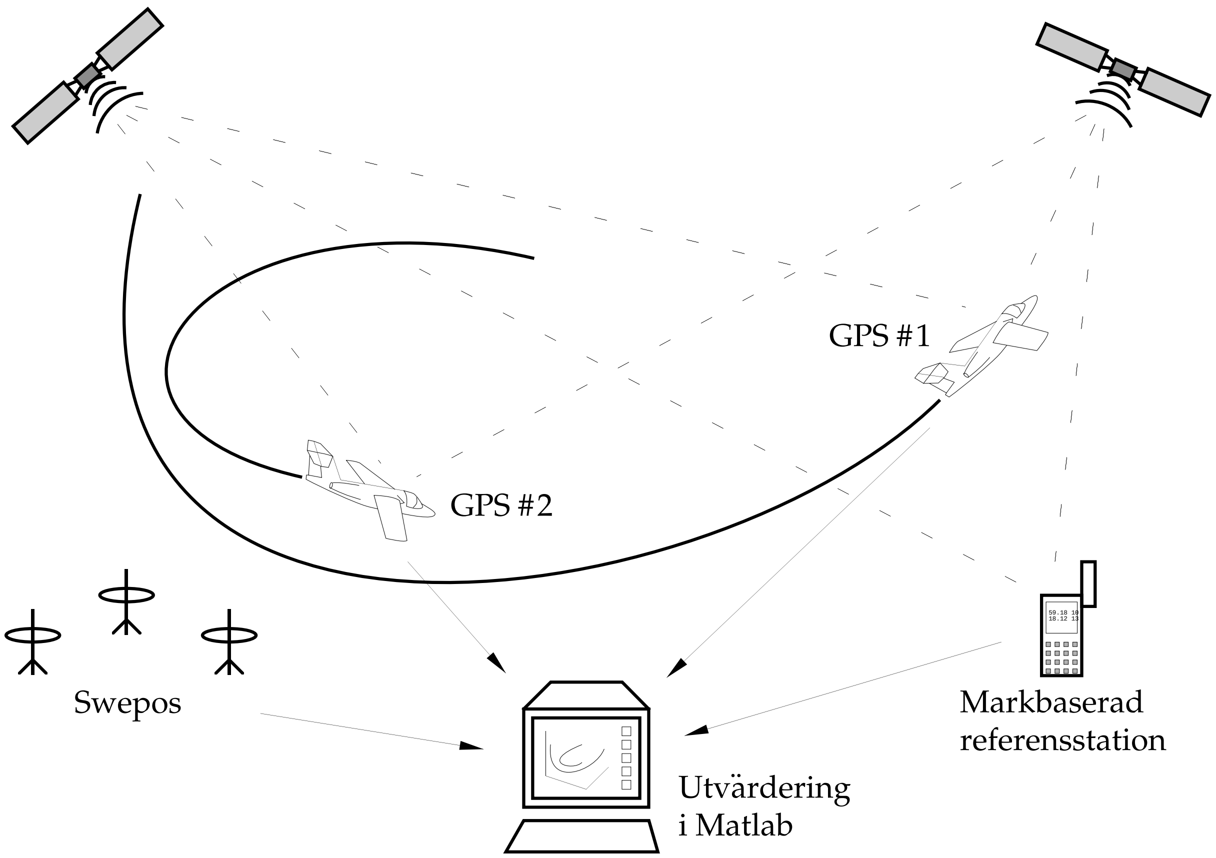
Final condition

Altitude 9 km
Mach 0.68

Mission evaluation

- J35/SK60 has no recording of flight data
- GPS only alternative (cost)
- Use optimization in reverse
- Measure some states with GPS
- Weather and winds from the weather service
- Estimate remaining states and controls with a simulation model

GPS-based evaluation system



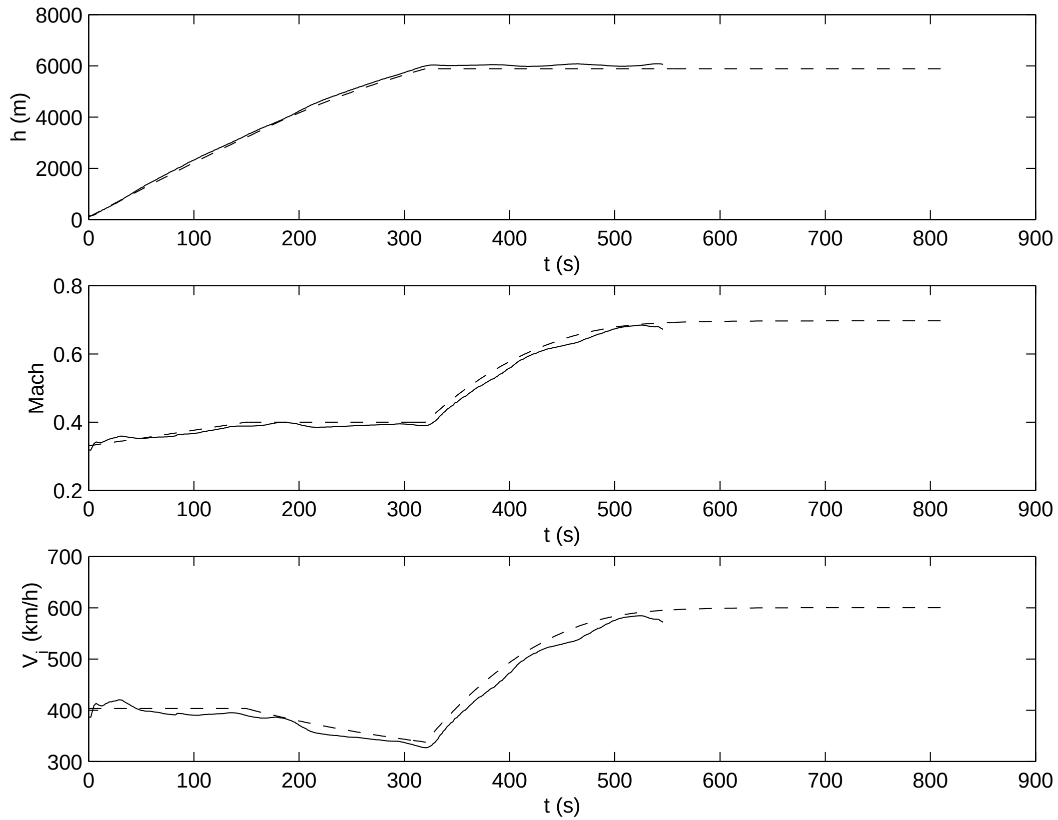
GPS requirements

- Handheld
- Internal (full) data storage, at least 1 hour
- Differential correction (DGPS) after flight
- Local base station or SWEPOS
- Software

Late -98: Trimble GeoExplorer II (III), Garmin 100 SRVY II

Flight manual climb for the SK60

Numerical model (- - -), GPS measurement (——)

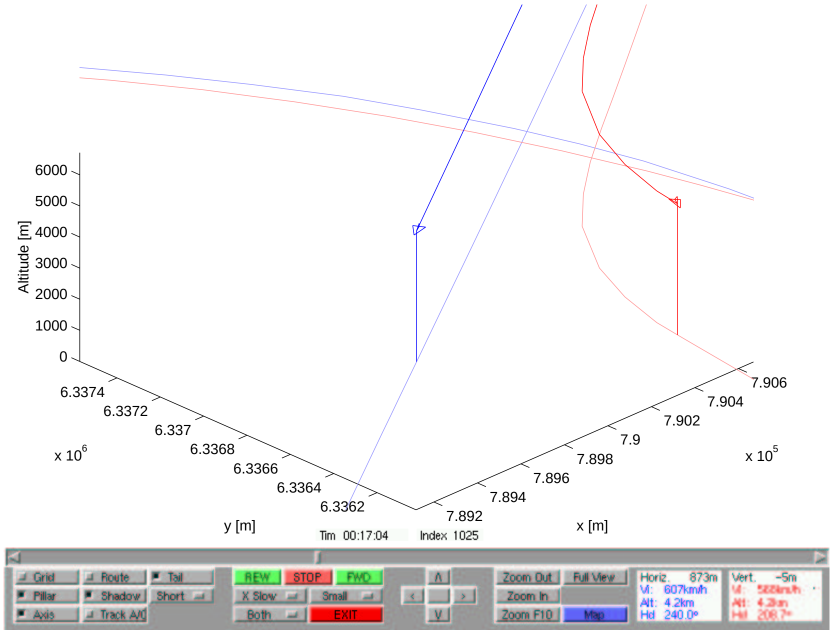


Postprocessing of GPS data

- The trajectory is known (x(t),y(t),z(t))
- Velocities and accelerations are estimated
- Weather model
- Simulation model
- Estimate:

  Angle-of-attack
  Attitude
  Load factor
  Thrust setting
  Fuel burn

Visualization



Matlab

OpenGL

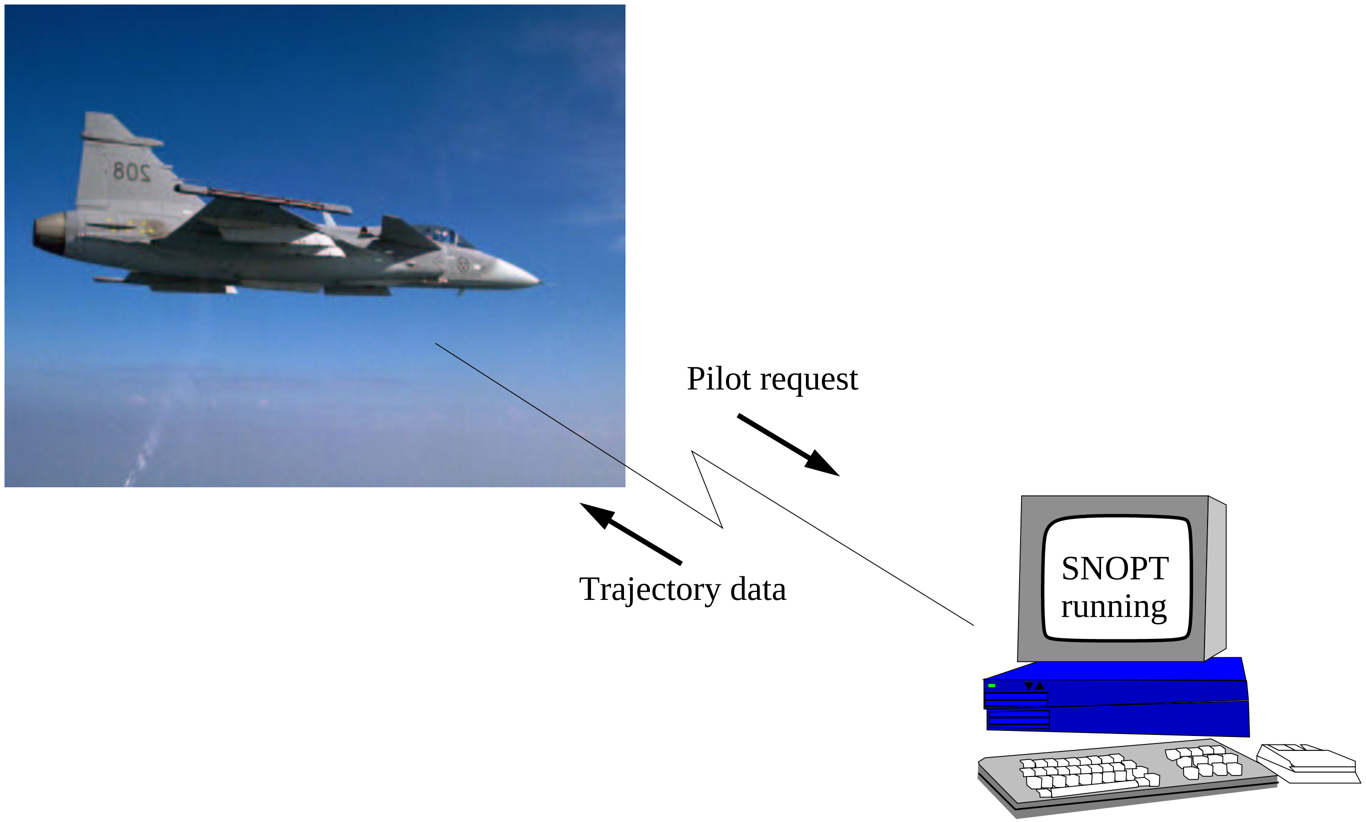
Developments

- Experiments with integrated GPS/INS
- Refined methods for the inverse problem
- Flight test data used for model verification
- Improved visualization
- Demonstrator for mission planning/evaluation for the SK60
- Collaboration with the Swedish Air Force

Future developments

- Modeling of weather and air space restrictions
- The pilot interface
- Autopilot for automatic path following
- Closed loop control
- Nonlinear optimization in close to real time
- Simple and robust methods for approximate solution
- Complex model and efficient methods for refined solution
- Modeling, numerical analysis, optimization and flight testing

Remote computation



Reverse processing improves the model

Unknown parameters p, e.g. $C_{L\alpha}$, in $\dot{x} = f(x, u, p)$

Measure state $\hat{x}(t)$ and control $\hat{u}(t)$ in flight testing

Solving $\dot{x} = f(x, u, p)$ gives $x(t, p)$ and $u(t, p)$

Find p that minimizes the differences $x(t, p) - \hat{x}(t)$ and $u(t, p) - \hat{u}(t)$