Icing Encounter Flight Simulator

Principal Investigator: Michael Selig

Graduate Students: Bipin Sehgal

Robert Deters*

Undergraduate Students: Michael Savchenko†

* Started January 2001

† From March 2001 – May 2001

SMART ICING SYSTEMS Research Organization

Core Technologies

- Aerodynamics and Propulsion
- Flight Mechanics
- Control and Sensor Integration
- Human Factors
- Aircraft Icing Technology

IMS Functions

- Characterize Icing Effects
- Operate and Monitor IPS
- Envelope Protection
- Adaptive Control

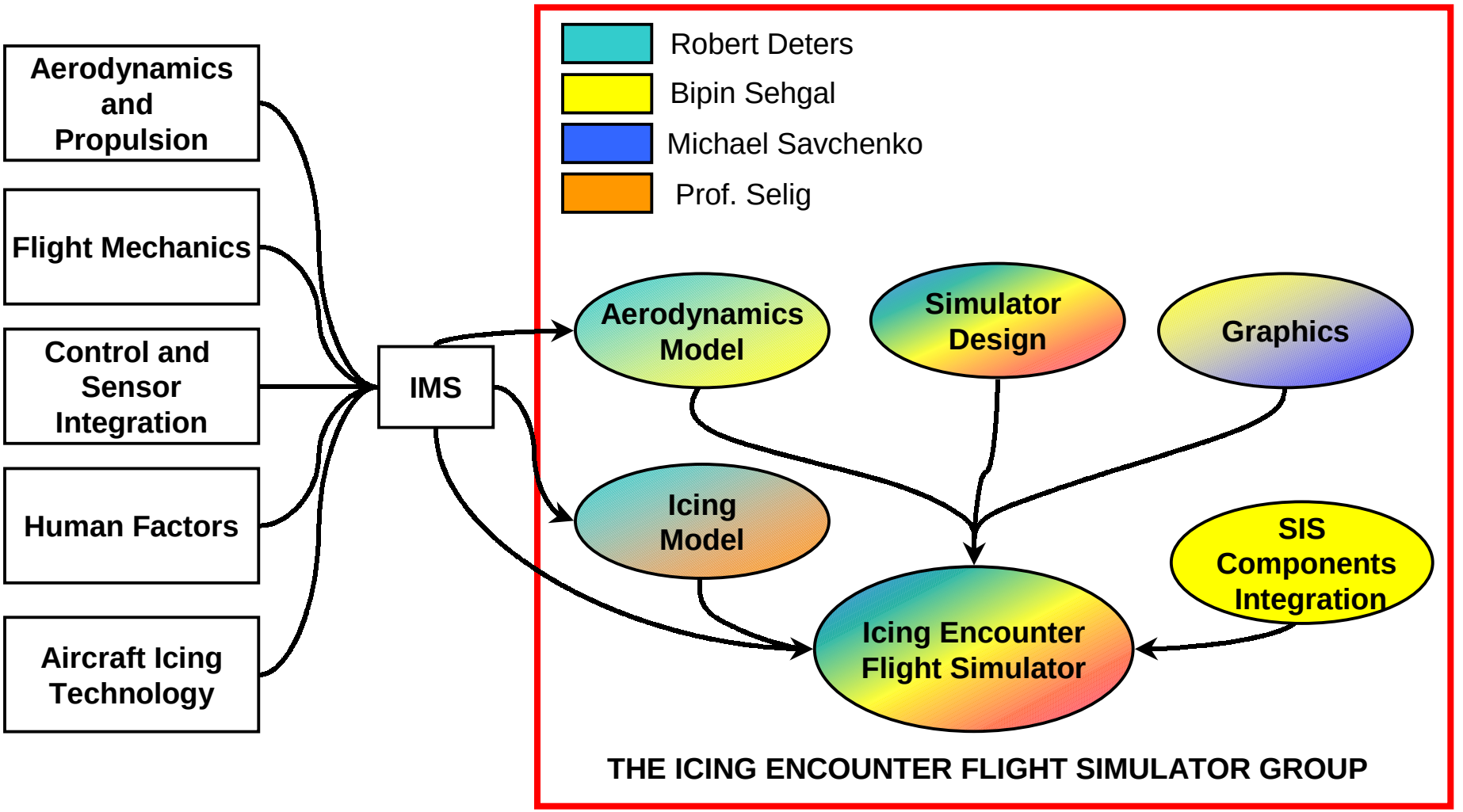
System Integration

- Flight Simulation
- Flight Test

Icing Encounter Flight Simulator

- **Goal:**
  - Improve the safety of aircraft in icing conditions.
- **Objectives:**
  - Function as a **systems integrator** by bringing together the various flight simulator components composed of an aircraft model, flight mechanics, aerodynamics, propulsion, controls, sensors, the ice protection system, the smart icing system, and human factors
  - Perform **"virtual flight tests"** to examine the effects of icing on aircraft operations under a variety of conditions
- **Approach:**
  - Develop an Icing Encounter Flight Simulator
  - Apply the simulator to icing scenarios and experiments

SMART ICING SYSTEMS Research



Outline

Bipin Sehgal:

Project Overview

Flight Gear Flight Simulator (FGFS)

UIUC-FGFS

- Code Organization
- SIS Components Integration

Graphics

Robert Deters:

UIUC-FGFS

- Aircraft Model
- Icing Model

Simulator Usage

Michael Selig:

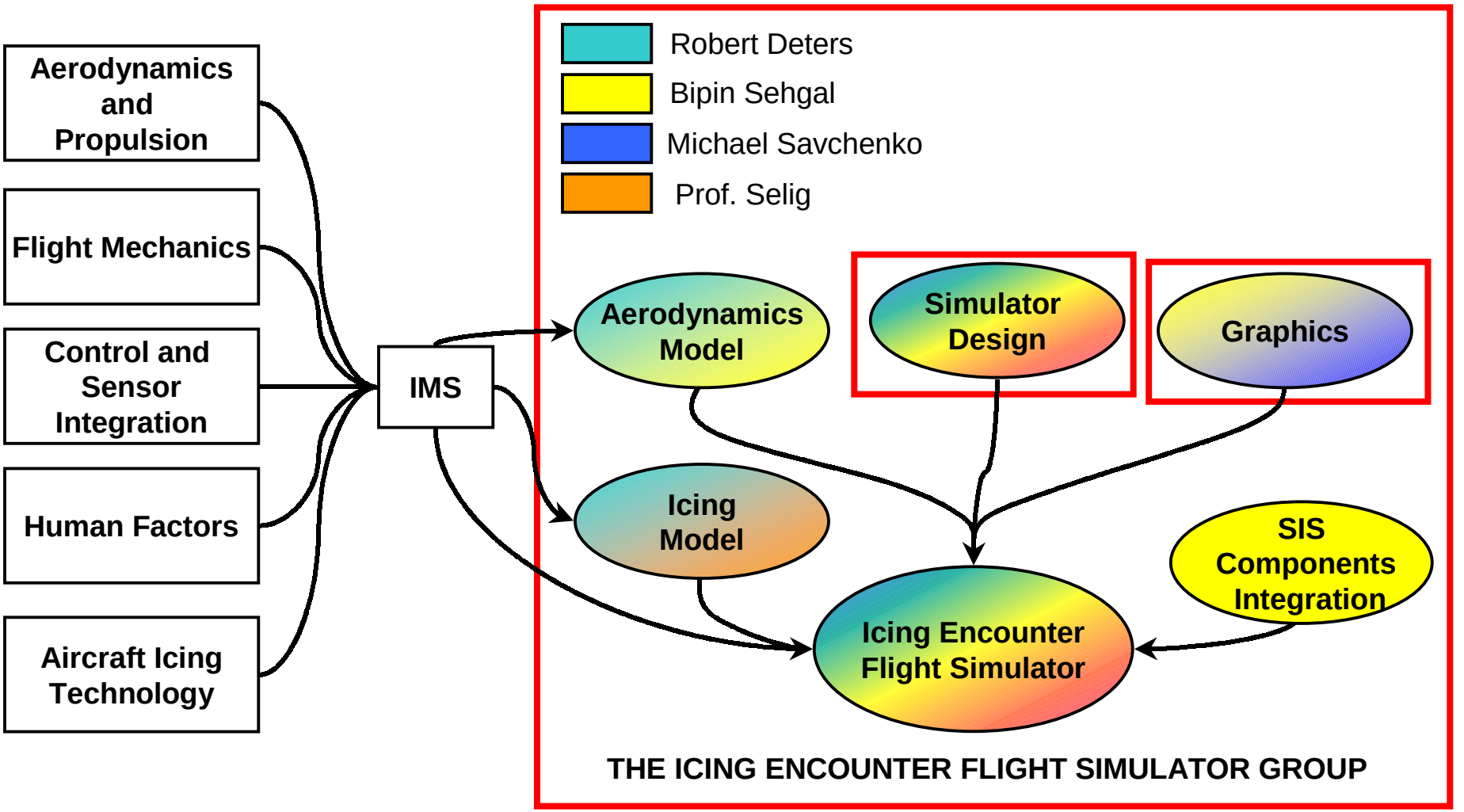
Demonstration

Conclusion

Progress as of Previous Review

- Improvement to the aerodynamics model
- Integration of SIS components
  - Icing model
  - Parameter ID algorithm
  - Hinge moments
  - Icing characterization neural network
- Improved graphics and features

SMART ICING SYSTEMS Research



Flight Gear Flight Sim (FGFS)

- Project started July 1997 (led by Curt Olson of Univ. of Minnesota Human Factors Lab)
- Cooperative development, over 50 people have contributed (http://www.flightgear.org)
- Free code, open-source, C/C++, about 100,000 lines of code, adheres to GNU General Public License (GPL)
- OpenGL graphics
- Multi-platform:
  - Windows NT/2000 (i86 platform)
  - Windows 95/98
  - Linux (any platform)
  - BSD Unix
  - SGI IRIX
  - SunOS
  - Macintosh

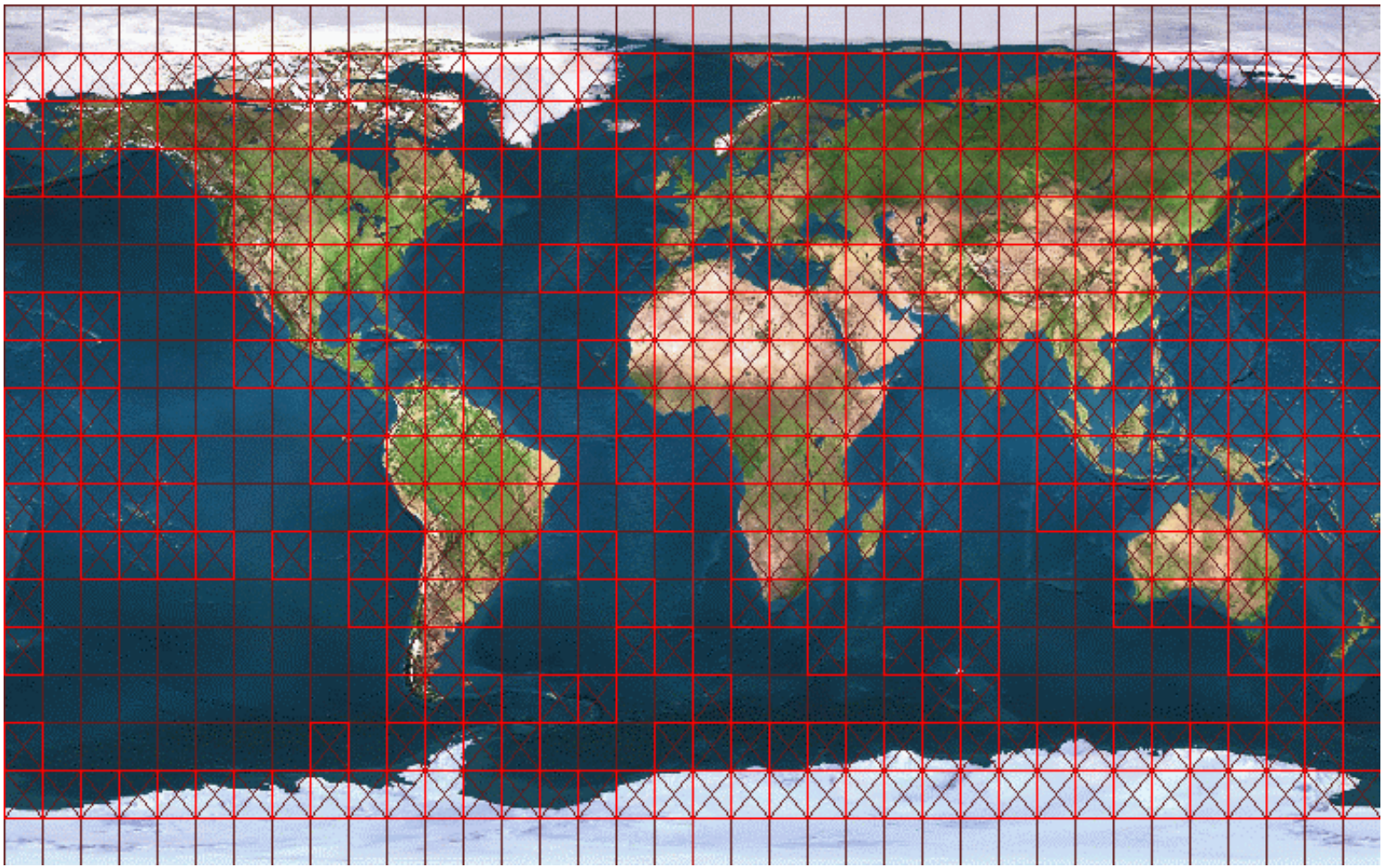
Flight Gear Capabilities

- Pilot input options:
  - Keyboard
  - Mouse (operates as joystick)
  - Joystick, throttle, rudder pedals
- Flight dynamics model:
  - Uses NASA Langley LaRCsim (Bruce Jackson, NASA TM 110164, Apr. 1995)
  - Models full 6-DOF nonlinear equations of motion (Richard McFarland, NASA CR-2497, Jan. 1975)
  - Uses quaternions for coordinate transformation

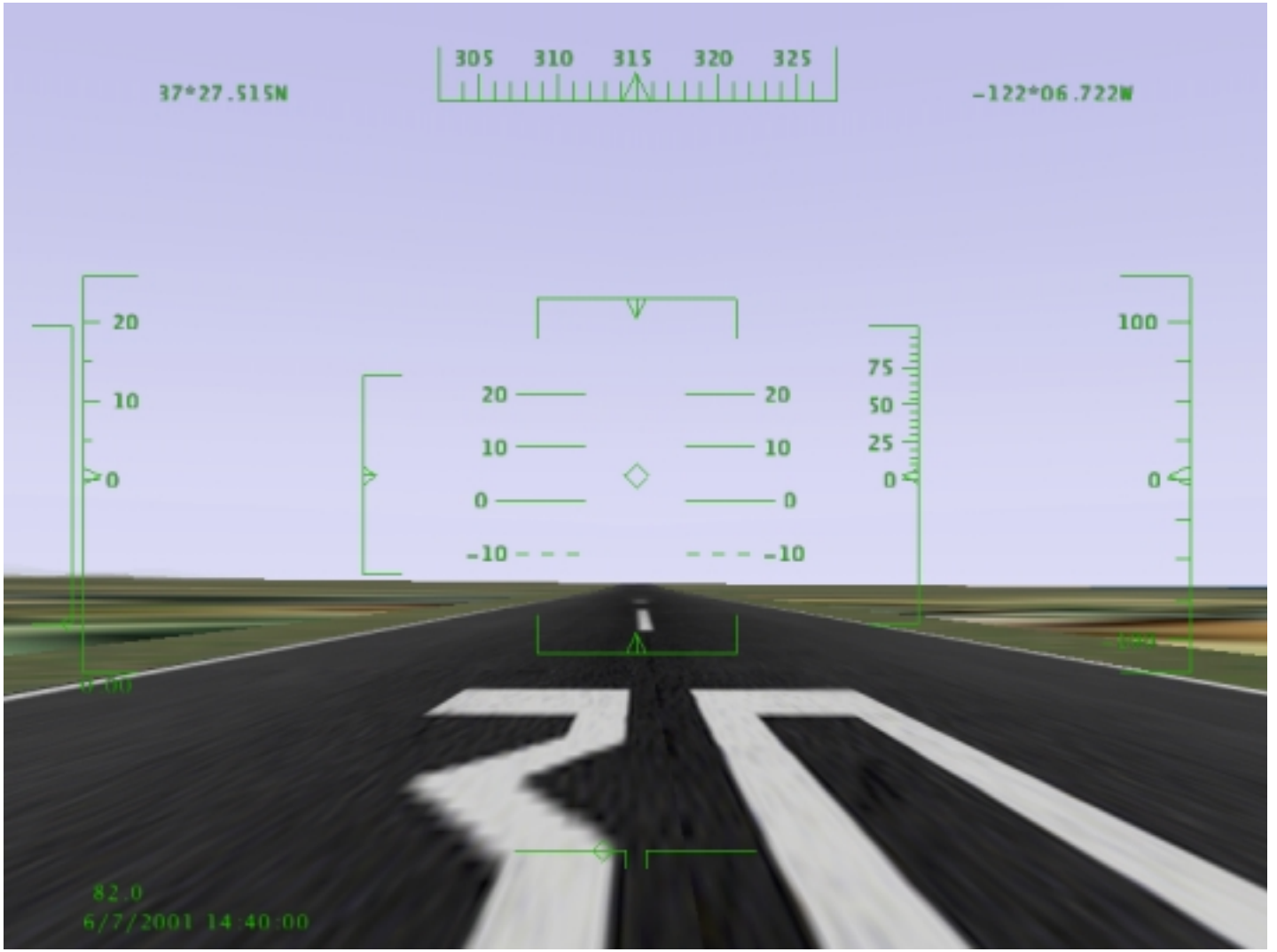
Flight Gear Capabilities

- Aircraft models:
  - Navion
  - Cessna 172
  - Cherokee
- Autopilots:
  - Altitude hold
  - Heading hold
  - Configured for Navion aircraft model only
- Views:
  - Instrument panel add-on
  - Realistic out-of-cockpit terrain view with HUD
  - Additional world scenery downloads available

Downloadable Scenery

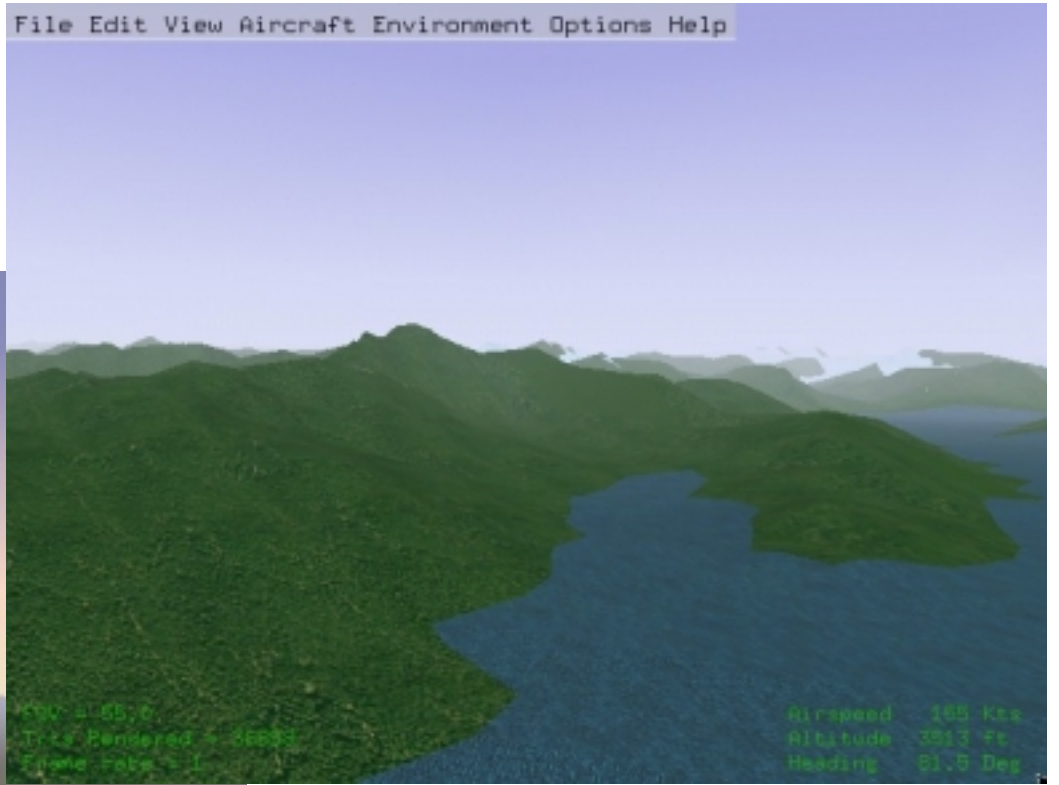


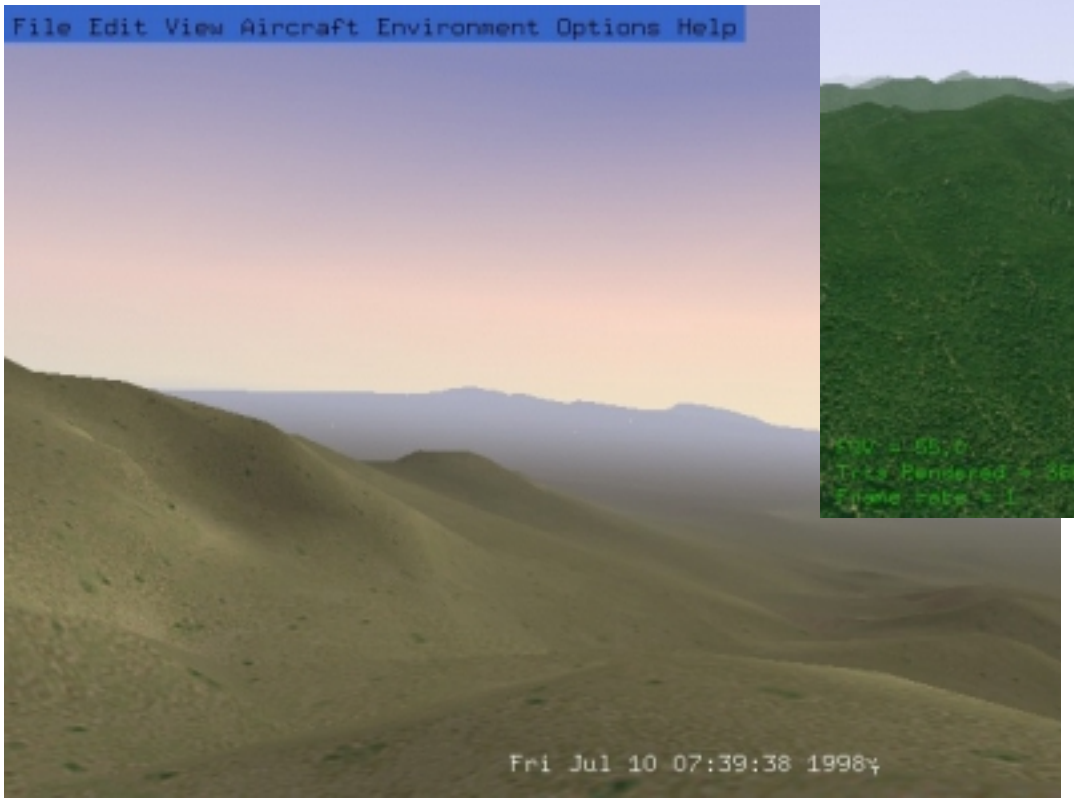
Sample Screen Grab – On Ground



Flight Gear Graphics

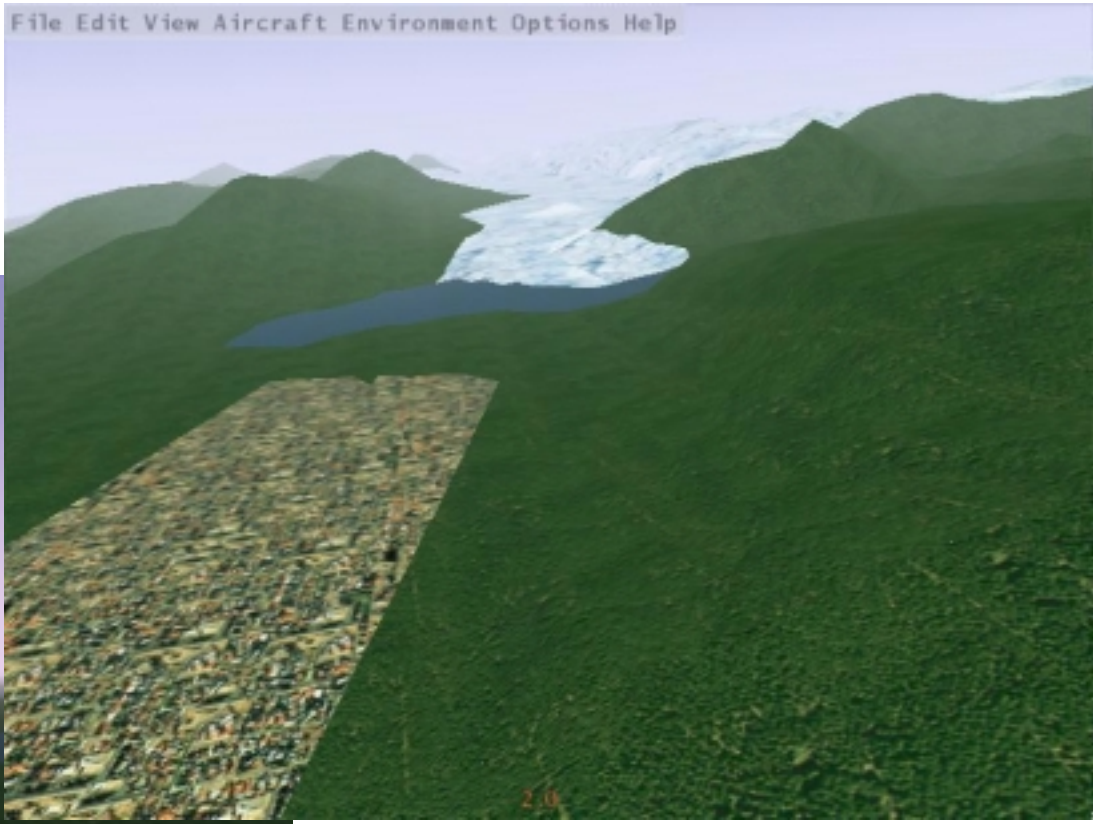
Mountains and Deserts

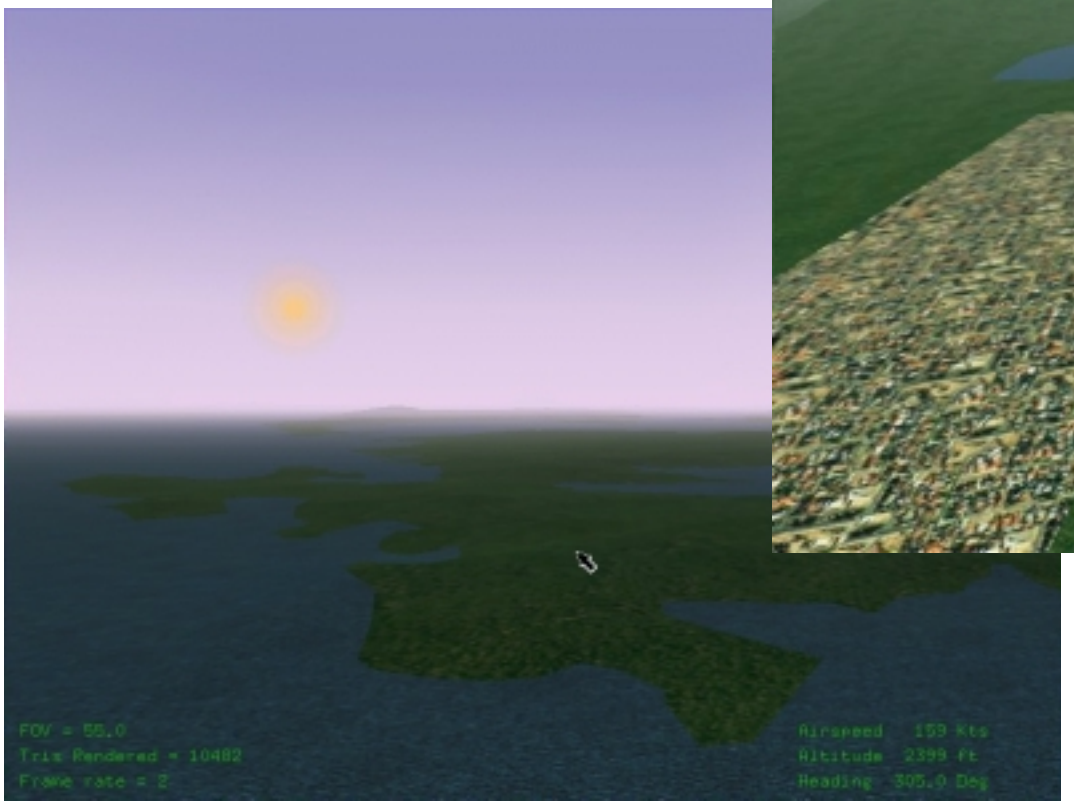




Flight Gear Graphics

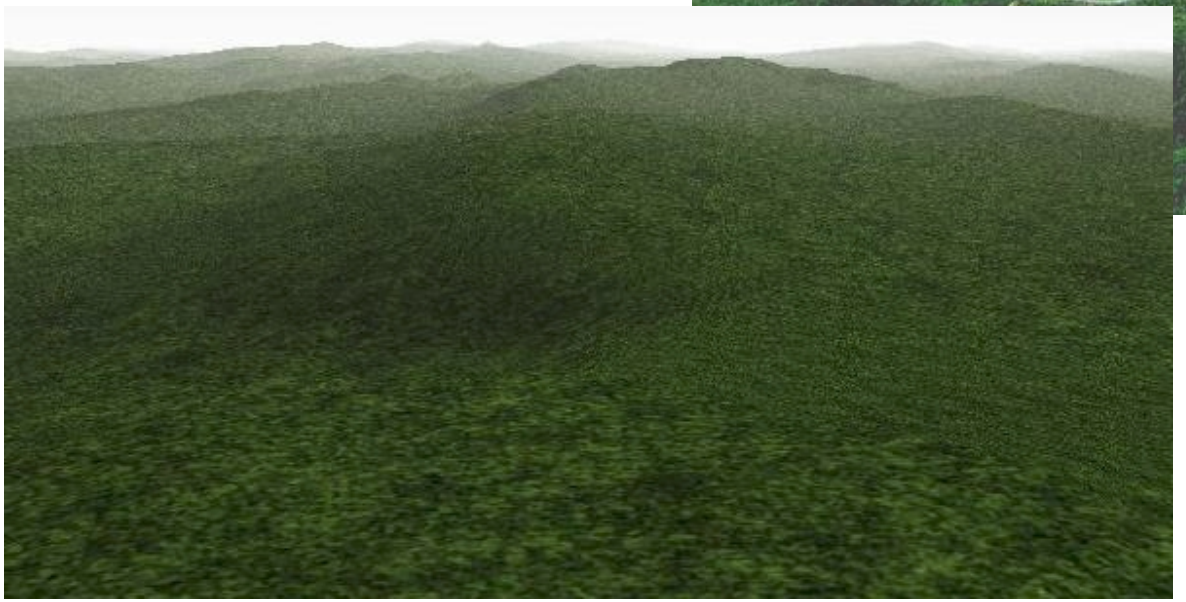
Cities, glaciers, bodies of water, Sun





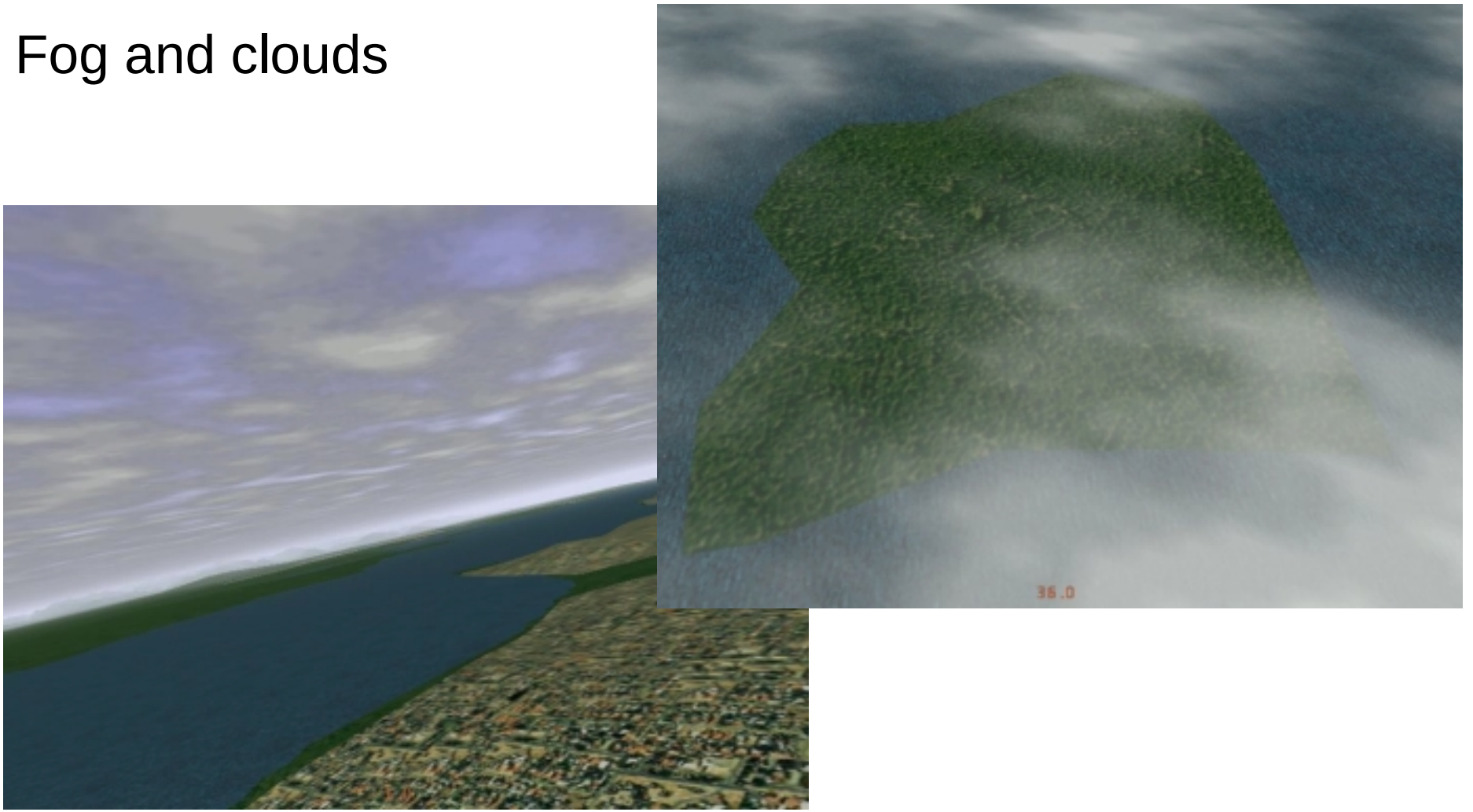
Flight Gear Graphics

Actual vs. simulated terrain



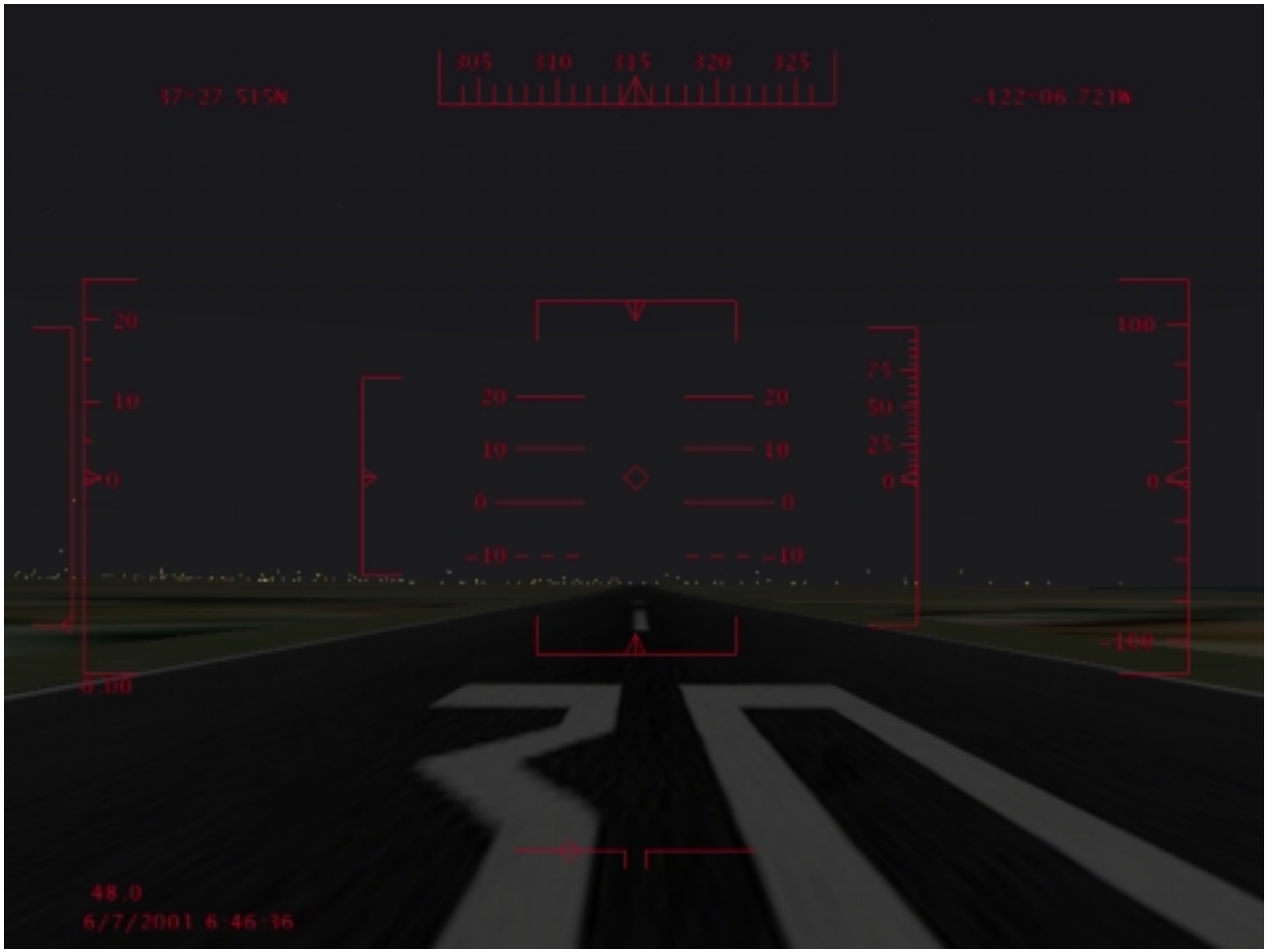
Flight Gear Graphics

Fog and clouds

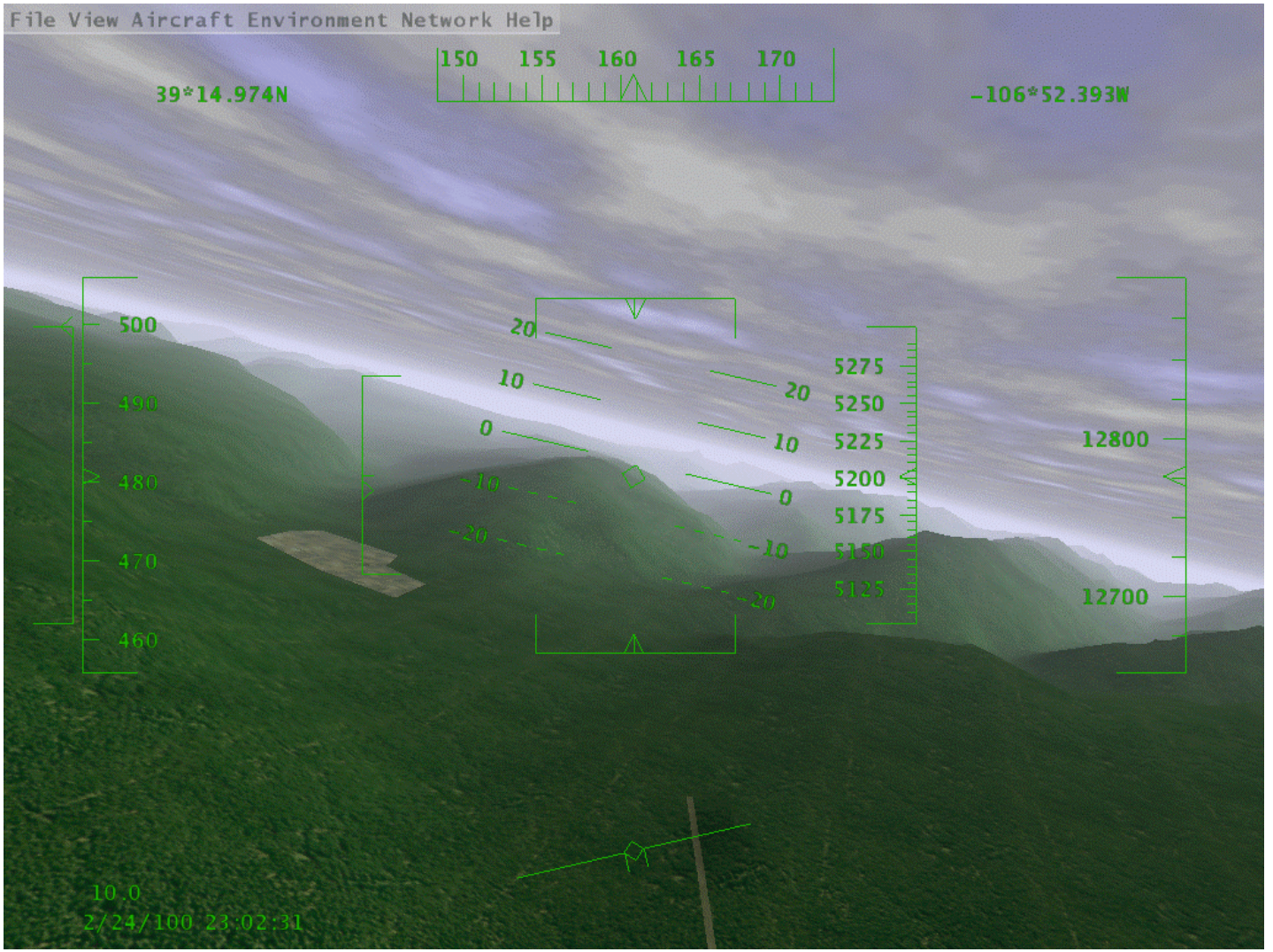


Flight Gear Graphics

Night view



Sample Screen Grab - In Flight



Recent Scenery Improvements

Three Panel Flight Gear Setup

Flight Gear Requirements

- Compiling tools:
  - Mesa (OpenGL clone)
  - Portable game library (plib)
  - Automake and autoconf (require perl)
  - Windows 95/98/NT/2000
    - Cygwin (UNIX shell environment for windows)
    - MSVC++
  - Linux (Redhat 7.1)
    - MATLAB 6.0 compiler and math library (for neural network code)

Flight Gear Requirements

- Development tools:
  - Source Navigator
  - Linux, Windows NT 4.0 (Cygwin 1.3)
  - GNU C++ compiler
  - MATLAB 6.0 for Linux
    - MATLAB compiler
    - MATLAB C++ math library

UIUC-FGFS

- Platforms:
  - Windows NT
  - Linux (Redhat 7.1)
- Based on Flight Gear 0.7.6
- Current capabilities:
  - Reconfigurable aircraft flight model
  - User can load aircraft-specific data at runtime using keyword-based input file
    - Linear stability derivatives
    - Nonlinear tabulated data (linear interpolation)

UIUC-FGFS

– About 20 aircraft models available, including:

- Twin Otter (a)
- Beech 99
- Pioneer UAV (b)
- Cessna 172
- Marchetti S-211
- Learjet 24
- Convair 880
- Boeing 747 (c)
- F-4 Phantom II
- F-104 Starfighter (d)
- X-15 (d)

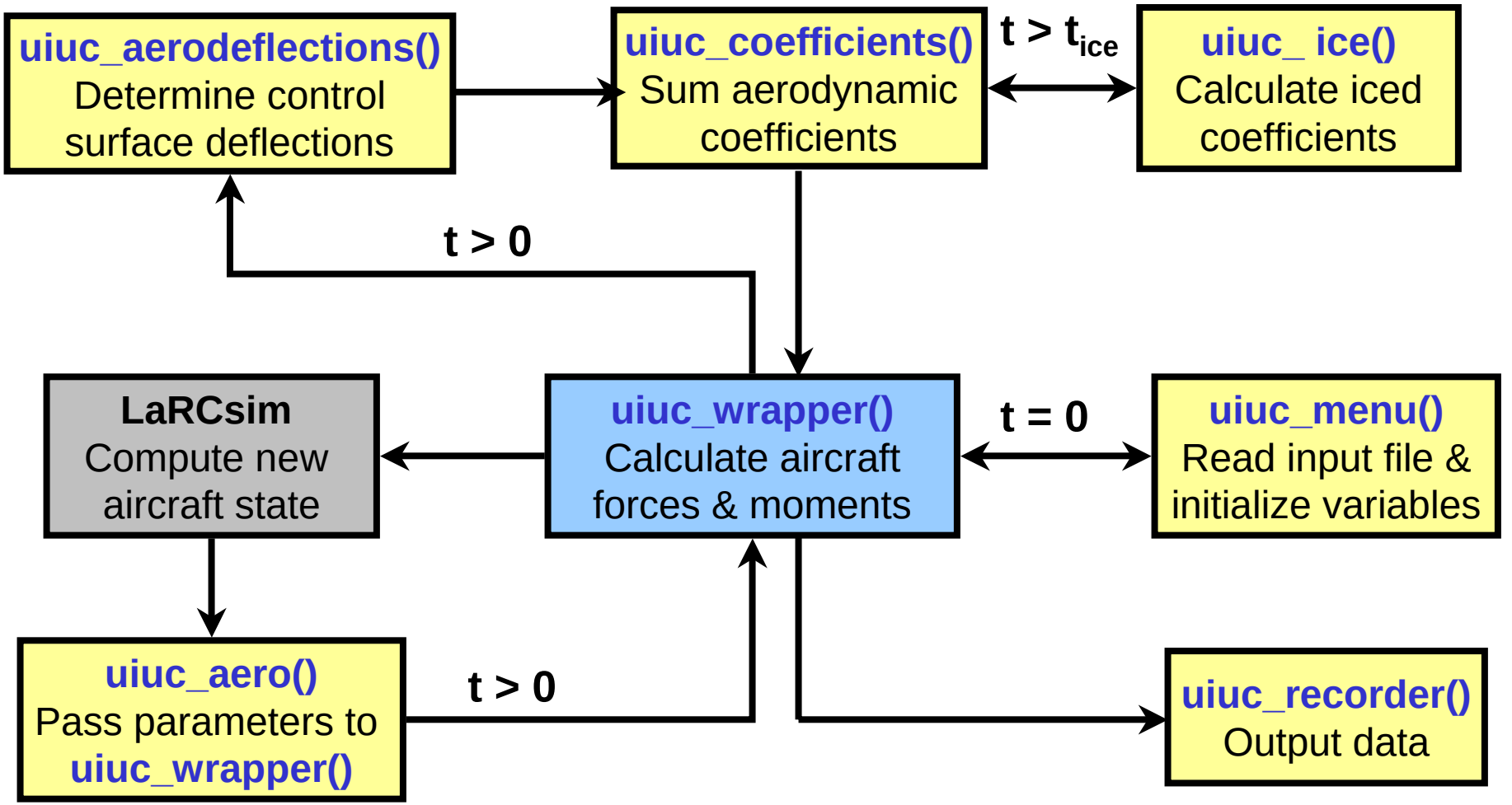
UIUC-FGFS

- Icing characterization (linear k_C_ η_{ice} model)
- Flight data recorder
- Networked instrument views building on Brian Fuesz's (Frasca) WinPioneer code
- Multiple aerodynamic model formats accepted:
  - Standard linear model (Roskam)
  - FDC (Twin Otter) linear model (Rauw)
  - Pioneer nonlinear model (Bray)

Sample Input File Commands


```
init            recordRate      10       # [times/s]
geometry        cbar            6.50     # [ft]
controlSurface  de              20 20    # [deg]
mass            Weight          11000    # [lb]
mass            I_xx            16039    # [slug-ft^2]
engine          simpleSingle    2000     # [lb]
CD              CDo             0.360    # [-]
CD              CXo            -0.360    # [-]
CL              CZ_de          -0.608    # [1/rad]
CL              CLfade CLfade.dat 0 1 1 # [-,deg,deg]
Cl              Cl_dr           0.015    # [1/rad]
record          Simtime                  # [s]
record          Altitude                 # [ft]
record          Alpha_deg                # [deg]
controlSurface  elevator_doublet 10 240 2
```

UIUC Aircraft Model



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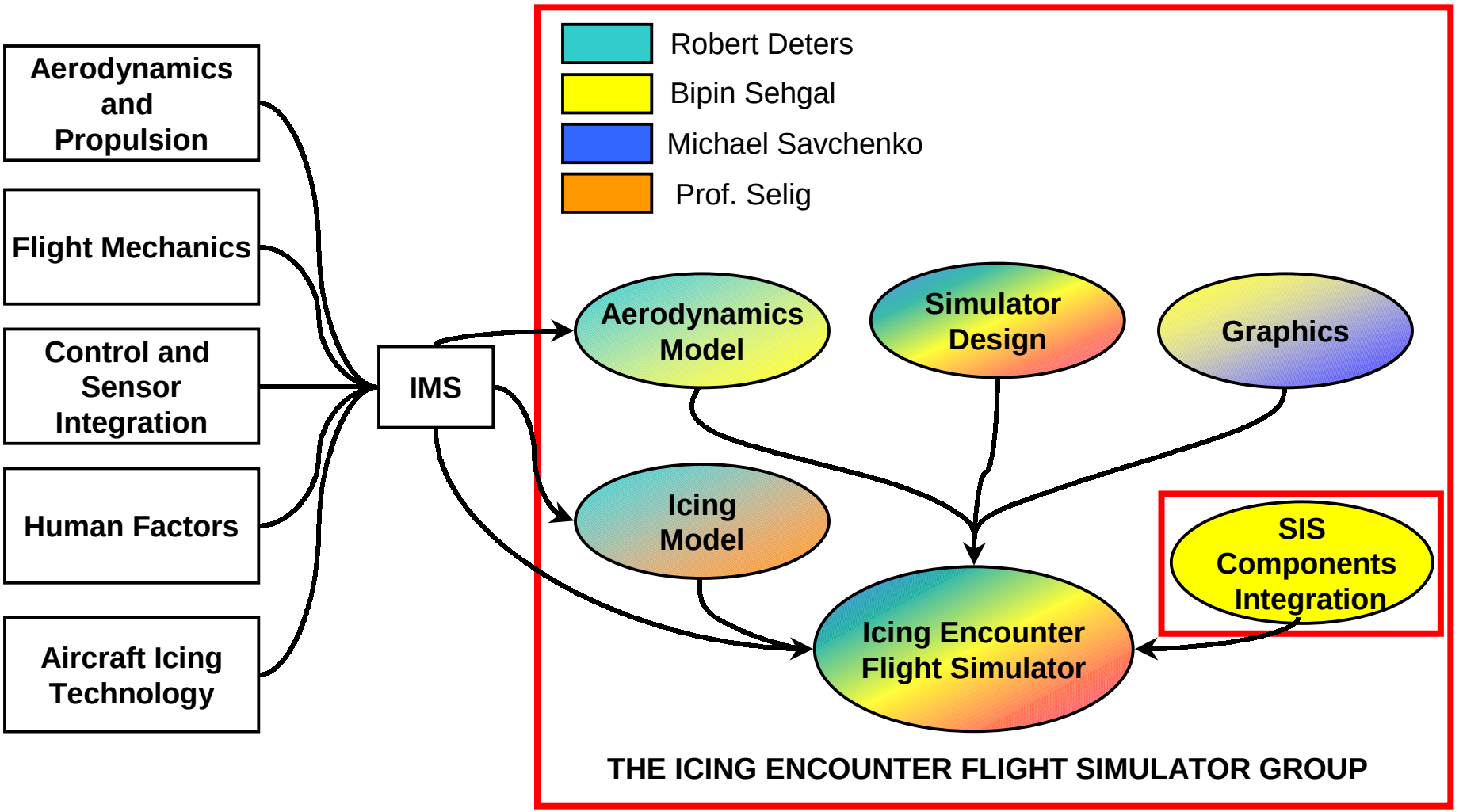
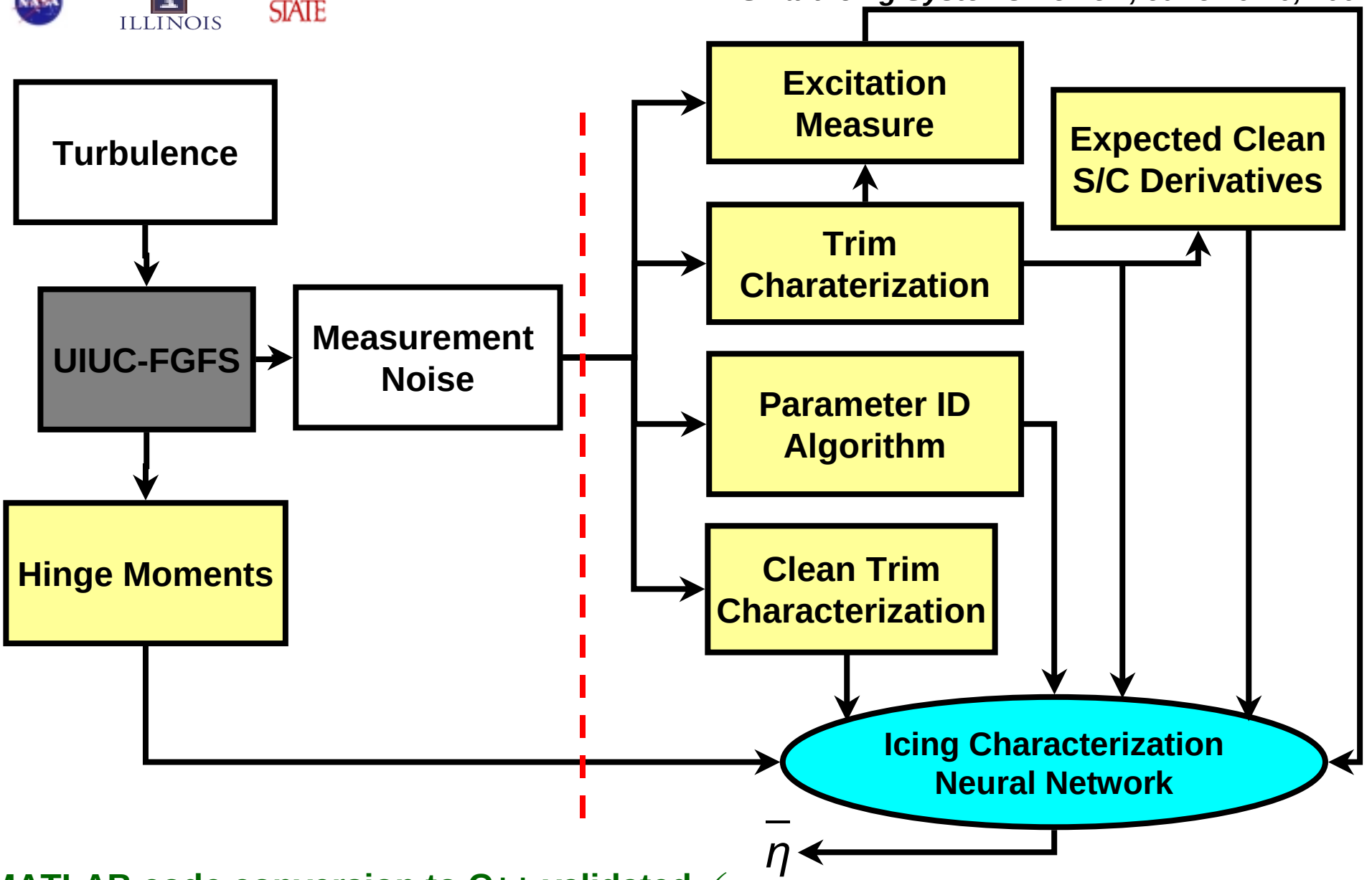


SIS Components Integration

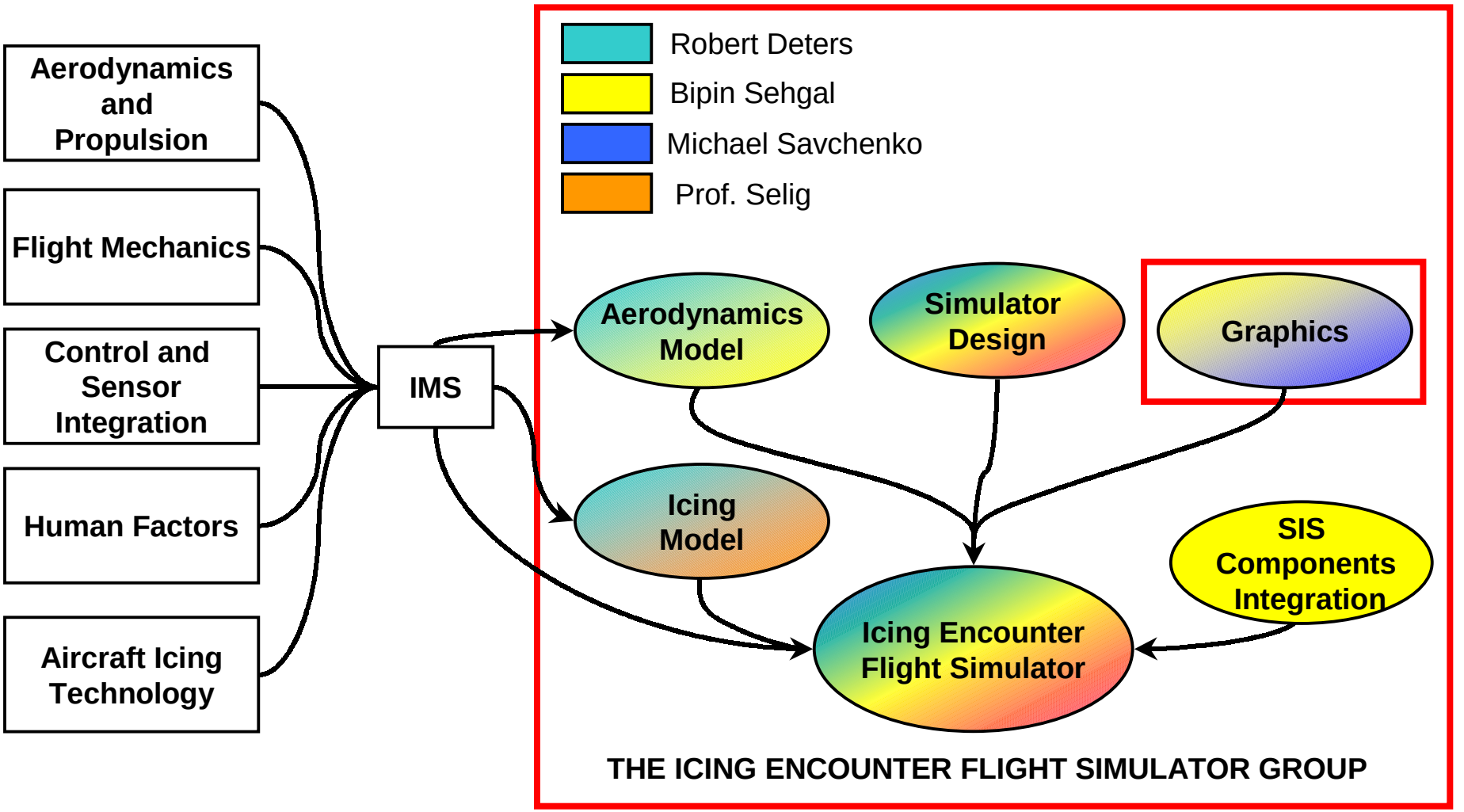
- MATLAB code for:
  - Hinge moments
  - Parameter ID algorithm
  - Icing characterization neural network
- Code converted into C++ using MATLAB APIs
  - Approximately 12,000 lines of C++ code
  - Need MATLAB compiler and math libraries for code conversion
  - Compiled using GNU C++ compiler

Neural Network Architecture



MATLAB code conversion to C++ validated ✓

SMART ICING SYSTEMS Research



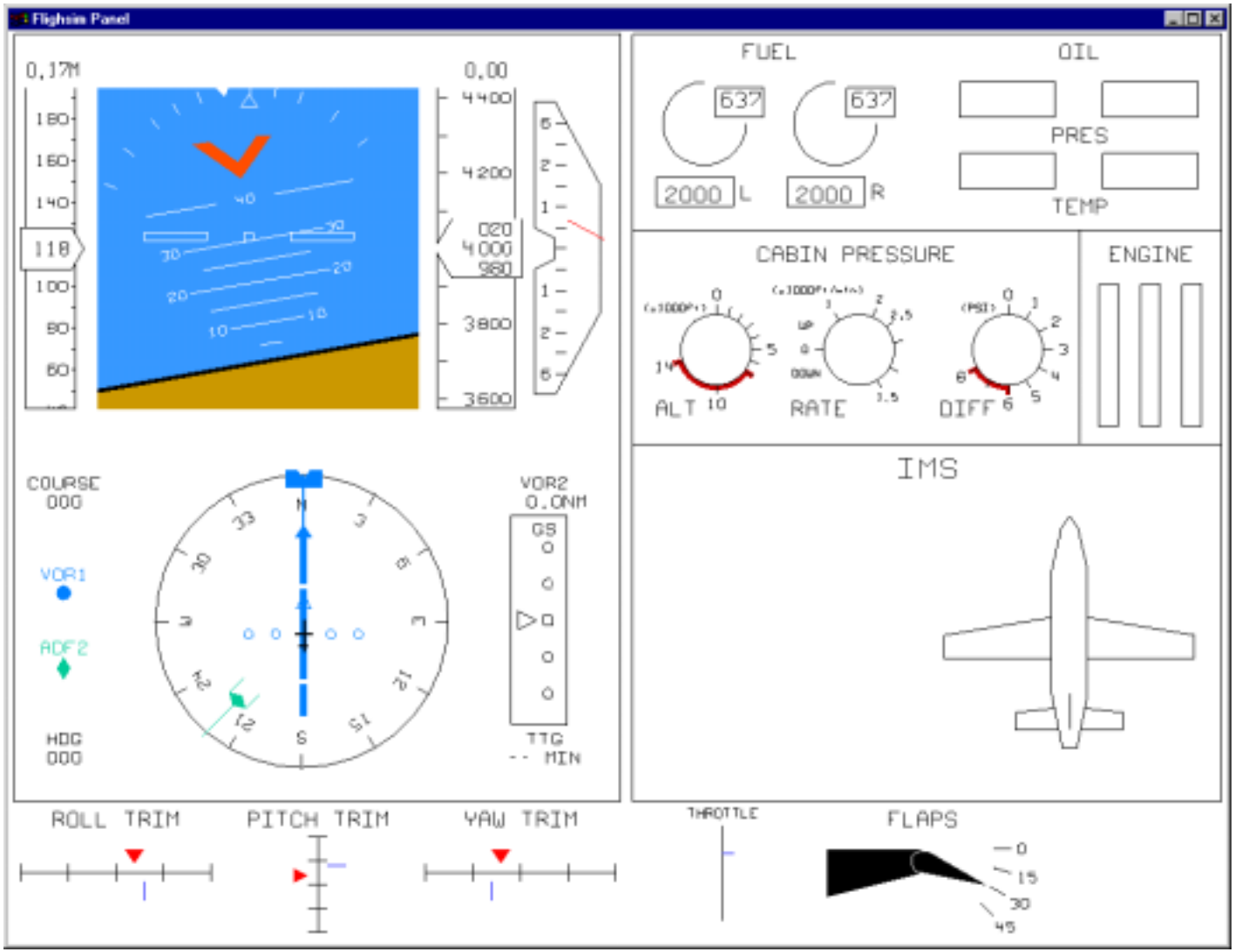
Graphics

- Switch to Flight Gear 0.7.6 (better graphics)
- Cloud appearance as a function of time (with icing)
- UIUC instrument panel
  - Human factors
    - What do we display to the pilots?
    - Design the IMS flight-deck display concepts
  - Implementation into OpenGL code
  - Integration with UIUC-FGFS

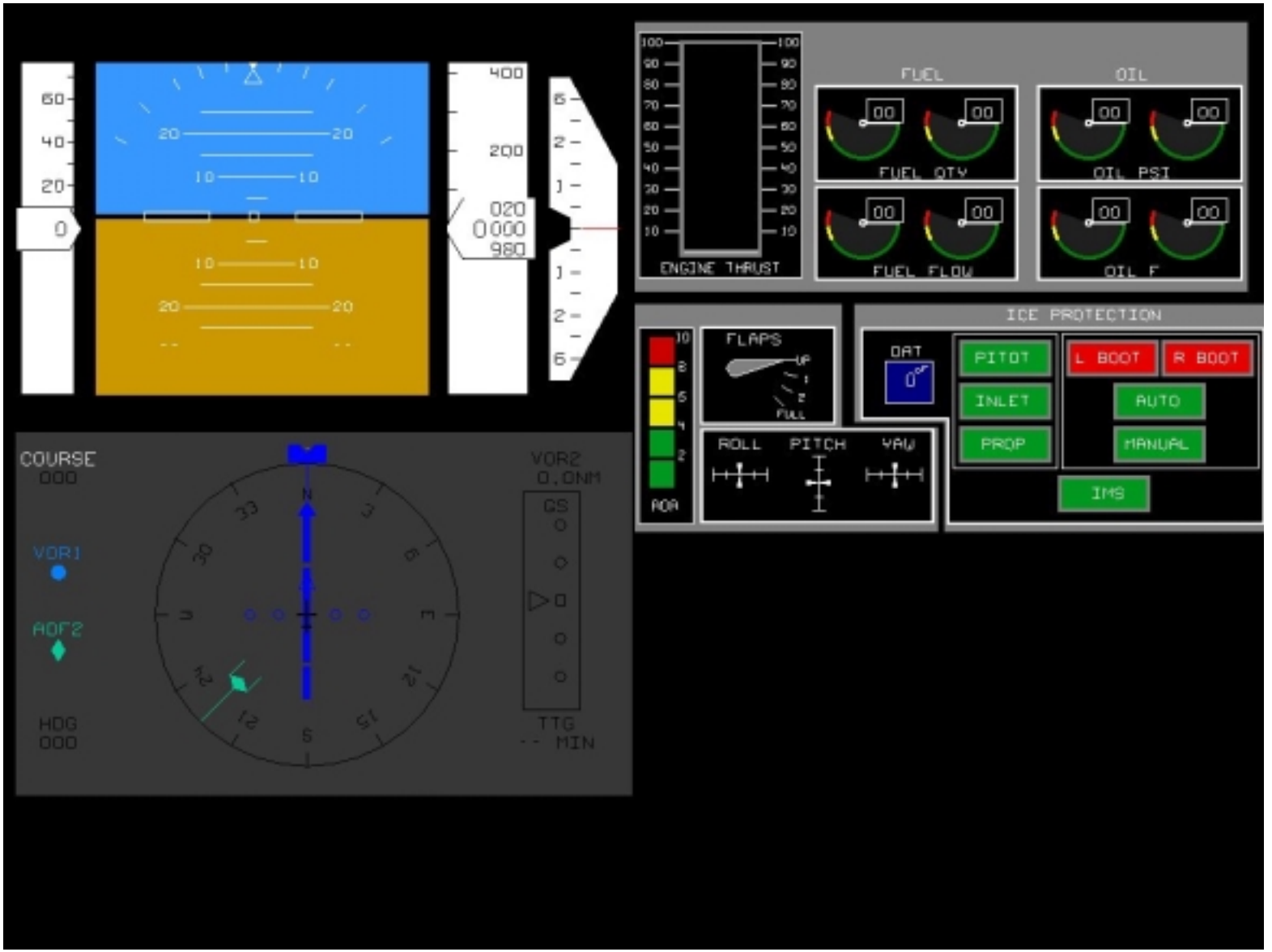
Instrument Panel

Flight Gear instrument panel

Glass Cockpit



New Glass Cockpit



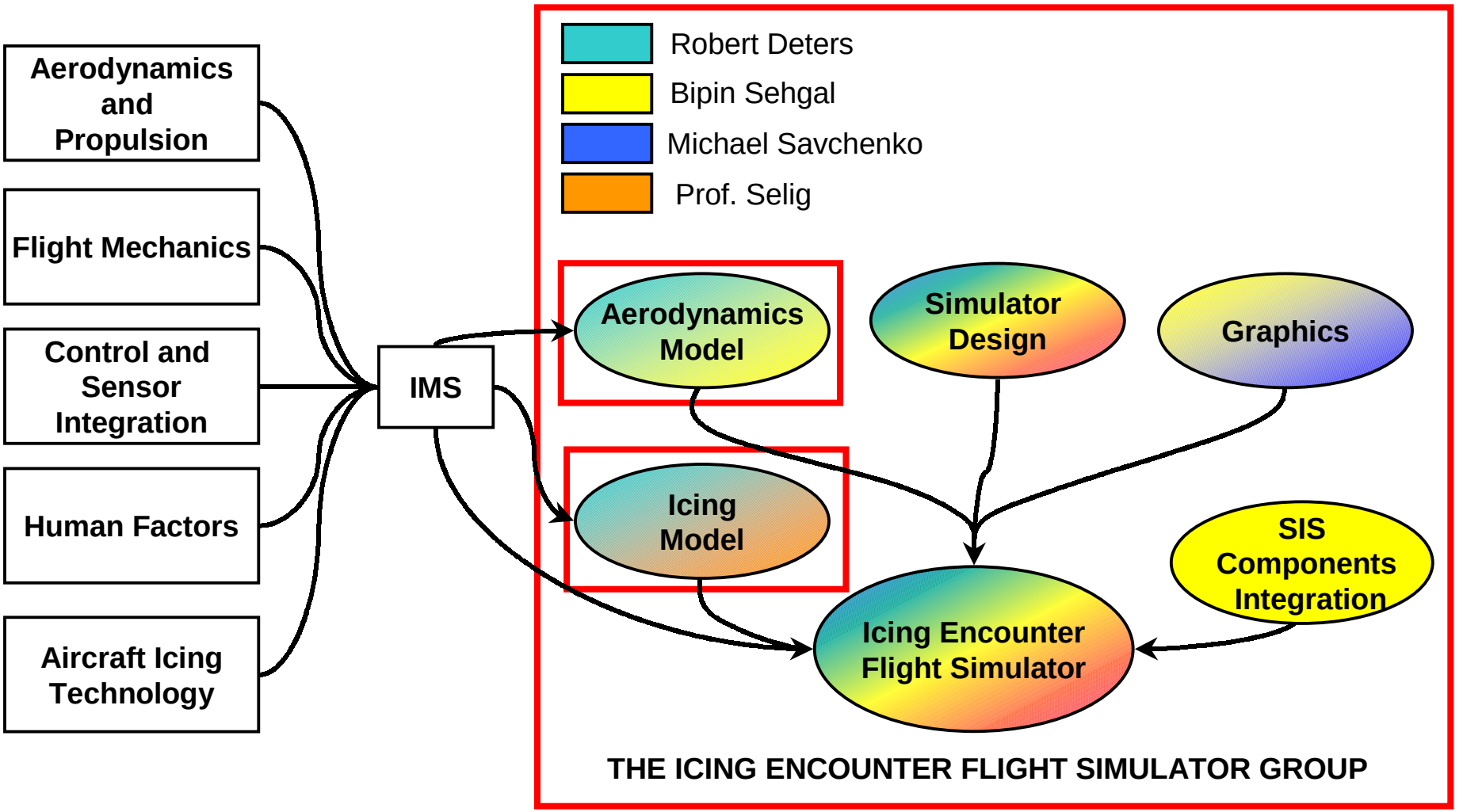
SIS Glass Cockpit

- Based on Brian Fuesz's implementation in WinPioneer
- OpenGL implementation under Linux
- Over the network on a different PC
- Ice detection based on $\bar{\eta}$ generated by the neural networks

Summary

- UIUC code adopted by Flight Gear group
- Basic aerodynamics model now functional
- Easy to add new aircraft models
  - Some 20 models already available
- Easy to expand code for new variables
- Ability to detect the onset of icing using neural networks

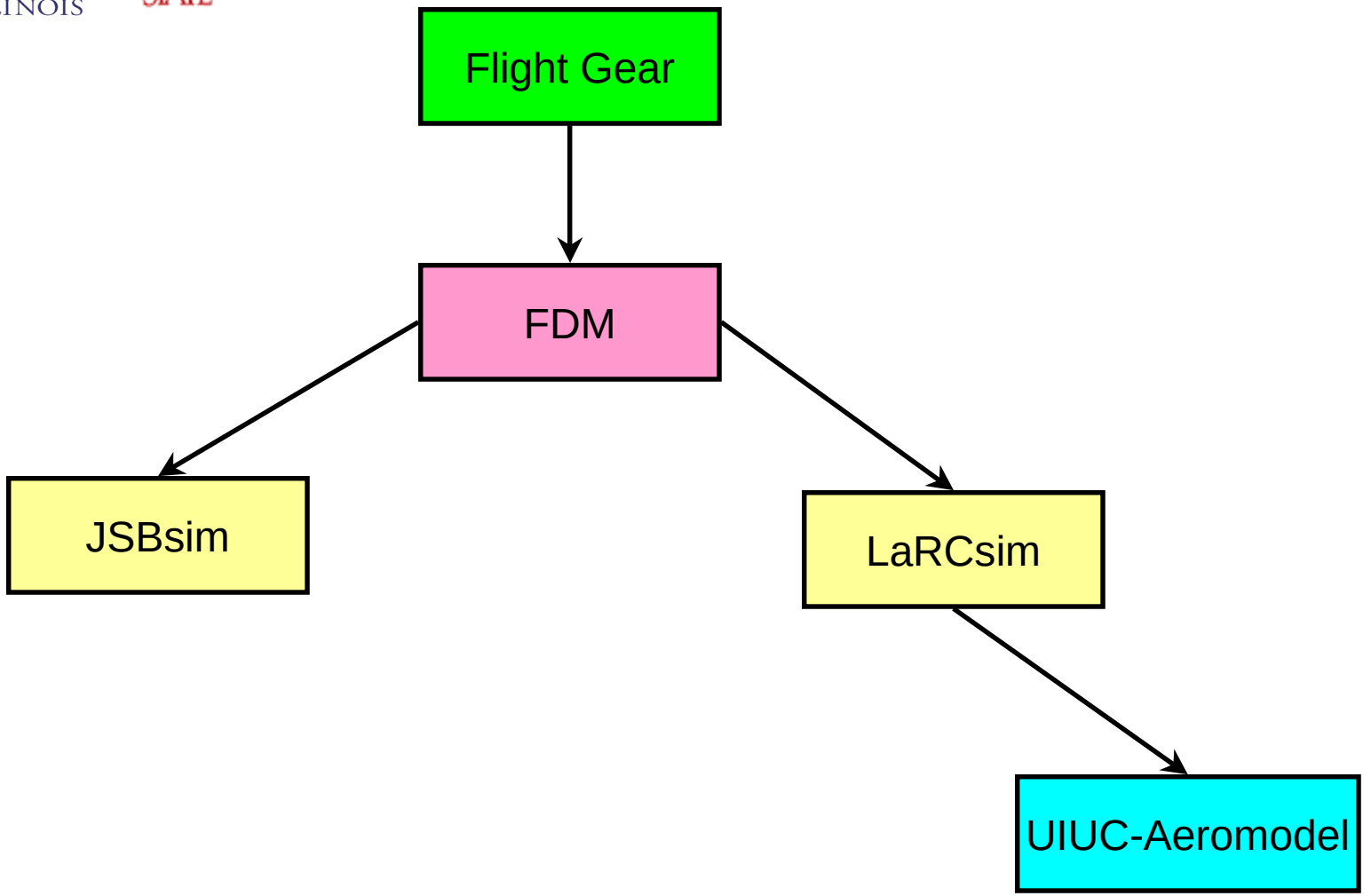
SMART ICING SYSTEMS Research



Outline

- Background Flight Dynamics
  - Code Layout
  - LaRCsim Module
- UIUC Aeromodel
  - Architecture
  - Icing Model
  - Gear Model
  - Validation Required Additions
- Summary
- Future Research

Flight Dynamics Module



LaRCsim Module

- LaRCsim flight dynamics model
  - Aircraft models:
    - Navion
    - Cessna 172
    - Piper Cherokee
  - Equations of motion:
    - Aerodynamic forces computed in the wind axis system:

$$F_{x\,wind} = -qSC_D$$

$$F_{y\,wind} = qSC_y$$

$$F_{z\,wind} = -qSC_L$$

LaRCsim Module

– Wind-axis to body-axis transformation gives the body axis forces:

$$\begin{bmatrix} F_{x\,aero} \\ F_{y\,aero} \\ F_{z\,aero} \end{bmatrix} = \begin{bmatrix} \cos\alpha\ \cos\beta & -\cos\alpha\ \sin\beta & -\sin\alpha \\ \sin\beta & \cos\beta & 0 \\ \sin\alpha\ \cos\beta & -\sin\alpha\ \sin\beta & \cos\alpha \end{bmatrix} \begin{bmatrix} F_{x\,wind} \\ F_{y\,wind} \\ F_{z\,wind} \end{bmatrix}$$

LaRCsim Module

– Aerodynamic moments computed in body axis system:

$$M_{lbody} = qSbC_l$$

$$M_{mbody} = qS\bar{c}C_m$$

$$M_{nbody} = qSbC_n$$

– Aerodynamic forces and moments summed with others acting on the aircraft:

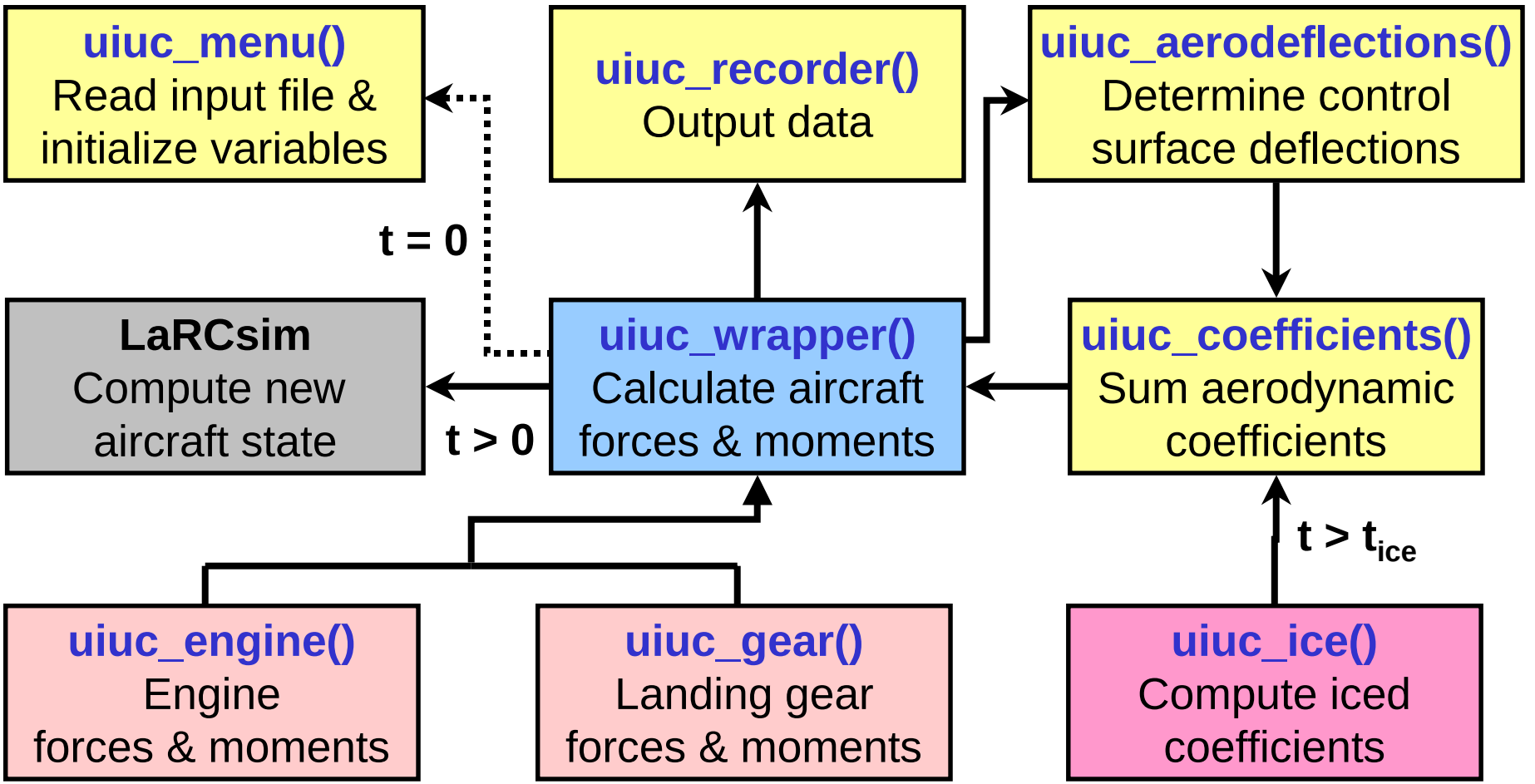
$$F = F_{aero} + F_{engine} + F_{gear} + \ldots$$

$$M = M_{aero} + M_{engine} + M_{gear} + \ldots$$

LaRCsim Module

- New aircraft state (i.e. roll, pitch, yaw rates, angle orientation etc.) determined
- LaRCsim adapted for UIUC aerodynamics model

UIUC Aeromodel Architecture



Icing Aerodynamics Model

- Applied η_{ice} model developed by Prof. Bragg's group
  - Twin Otter model

$$C_{(A)_{iced}} = (1 + \eta_{ice}\, k'_{C_{(A)}})\; C_{(A)}$$

Icing Aerodynamics Model

- Allows η_{ice} and icing constants ($k_{C\_}$) to be varied to model different icing cases
  - Wing icing
  - Tail icing
  - Aircraft icing
  - Overall icing severity

Sample of Different Icing Cases

	All Ice	Wing Ice	Tail Ice
kCXo	6.52696	2.64444	1.58844
kCX_a	-0.14296	-0.03156	-0.04504
kCZ_a	-1.48148	-0.83259	-0.36593
kCZ_de	-1.40741	-0.33970	-1.05556
kCm_a	-1.46667	-0.28346	-0.53244
kCm_de	-1.48148	-0.26504	-1.24756

Gear Model

- Created by David Megginson (FGFS) based on Tony Peden's (FGFS) work
- Configure landing gear by commands in the input file
  - Location
  - Damping constant
  - Spring constant
  - Rolling friction coefficient

Aerodynamic Model Additions

- Features added for flight test validation task
- Ability to start at any initial condition
  - FGFS command line inputs
    - Altitude, velocity (u,v, w), Euler angles (ϕ, θ, ψ)
  - UIUC input file commands
    - Angular velocities (p, q, r), control surface deflections (aileron, elevator, rudder), throttle, angle of attack, sideslip angle

Aerodynamic Model Additions

- Ability to run pre-made flight maneuvers
  - Basic maneuvers superimposed on stick flying
    - Elevator step, singlet, and doublet
  - Full flight test / complex maneuvers
    - Elevator, aileron, rudder, and throttle input files
      - Function of time
      - Linear interpolation between points

Simulator Usage

- Running the simulator
  - Need a good 3D accelerator card with full OpenGL drivers to achieve smooth frame rates
  - Runs through the command line or by using a batch file

Simulator Usage

emacs@AA16

Buffers Files Tools Edit Search Mule Help

```
rem @ECHO OFF

rem Skip ahead to CONT1 if FG_ROOT has a value
IF NOT %FG_ROOT%.==. GOTO CONT1

SET FG_ROOT=.

:CONT1

rem Check for the existance of the executable
IF NOT EXIST %FG_ROOT%\BIN\FGFS.EXE GOTO ERROR1

rem Now that FG_ROOT has been set, run the program
ECHO FG_ROOT = %FG_ROOT%

rem Twin Otter at Chicago (O'Hare Airport)
%FG_ROOT%\BIN\FGFS.EXE --aircraft-dir=Aircraft-uiuc/TwinOtter    --airport-id=KORD --heading=45

rem Marchetti trainer at Grand Canyon
rem %FG_ROOT%\BIN\FGFS.EXE --aircraft-dir=Aircraft-uiuc/Marchetti    --airport-id=25U  --heading=10
--d**  runfgfs.bat<2>   12:45PM   (Text Fill)--L18--C0--Top----------------------------------------
```

Sample Input File

emacs@AA16

Buffers Files Tools Edit Search Mule Makefile Help

```
init recordRate 4        # [/s]
#init recordStartTime 5  # [s]
init Dz_cg    2.5        # [ft]        FG c172_aero.c
init nondim_rate_V_rel_wind

geometry bw   35.8       # [ft]        FG c172_aero.c
geometry cbar  4.90      # [ft]        FG c172_aero.c
geometry Sw  174.0       # [ft^2]      FG c172_aero.c

controlSurface de 28 23 # [deg]        FG c172_aero.c
controlSurface da 20 15 # [deg]        FG c172_aero.c
controlSurface dr 16 16 # [deg]        FG c172_aero.c
controlSurface zero_Long_trim
#controlSurface set_Long_trim_deg 1.6598
#controlSurface elevator_doublet 10 240 2

mass Weight  2300.0      # [lb]        FG c172_init.c
mass I_xx     948.0      # [slug-ft^2] FG c172_init.c
mass I_yy    1346.0      # [slug-ft^2] FG c172_init.c
mass I_zz    1967.0      # [slug-ft^2] FG c172_init.c
mass I_xz       0.0      # [slug-ft^2] FG c172_init.c

engine c172

CL CL_adot  1.7          # [/rad]      FG c172_aero.c
CL CL_q     3.9          # [/rad]      FG c172_aero.c
CL CL_de    0.34763715   # [/rad]      FG c172_aero.c
CL CLfa ../Aircraft-uiuc/000504-Cessna172-TD2/CLfa.dat 0 1   # [] FG c172_aero.c

CD CDo      0.036        # []          FG c172_aero.c
--u**  aircraft.dat   12:27PM   (Makefile CVS:1.3)--L29--C0--Top----------------
Fontifying aircraft.dat...done
```

Summary

- Model ready for simulating flight tests
  - User specified initial conditions
  - Pre-made flight maneuvers
  - Control surface and throttle input files
- Began validation with flight test data
- Different icing cases ready for testing
  - Wing icing
  - Tail icing
  - Aircraft icing
  - Icing severity

Future Work

- Code maintenance: keeping up-to-date with the Flight Gear improvements
- Simulator improvements
  - Icing model
  - Engine model
  - Gear model
  - Nonlinear aerodynamics
  - Turbulence

Future Work

- Incorporate SIS components
  - Latest ID algorithm
  - Autopilot
  - Human factors
- Perform virtual flight tests for the Twin Otter to aid in the design of the next set of experiments

Flight Simulation Waterfall Chart