Spacecraft Simulation and Visualisation with Orbiter 2006

Martin Schweiger

Centre for Medical Image Computing
Department of Computer Science
University College London, UK

martins@medphys.ucl.ac.uk

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Contents

- Introduction
  - Orbiter overview
  - Orbiter 2006 - new features
- Simulation and physics engine
  - Dynamic state integration
  - Scenario editor
- Visualisation and graphics engine
  - Launcher and payload examples
  - Planetary surfaces
  - Interactive flightdeck simulation
- External trajectory data interface
  - Flight recording and playback
  - Playback of external data
- Orbiter demonstration

Introduction: Orbiter

- Real-time space flight simulation and visualisation on the PC
  - Under development for 6 years, latest version is 2006-P1 Edition.
  - Newtonian physics engine, numerical state integration including gravitational perturbation effects
  - Covers: atmospheric, suborbital, orbital, interplanetary flight
  - Demonstrate: launch, rendezvous/docking, re-entry, interplanetary transfers, gravity-assist, and more.
- Visualisation/demonstration tool
  - Interface to external trajectory data allows use of Orbiter as a visualisation tool, bypassing the internal physics engine
- Educational tool
  - Hands-on orbital mechanics demonstrator
- Development model:
  - Modular structure: core application provides physics and graphics engine
  - Extensive application programming interface (API) available for 3rd party addition of plugin modules (spacecraft, launch sites, celestial bodies, instrumentation, autopilots, remote control, networking, etc.)
  - An active development community has created an extensive collection of high-quality models of historic, hypothetical and fictional spacecraft.

Introduction - New features in Orbiter 2006

- Physics engine
  - Adaptive order of integration of linear and angular states (Runge-Kutta and symplectic integrators to order 8)
  - Perturbation model now includes gravity-gradient torque simulation
- User interface
  - Scenario editor for easy simulation setup
  - Instrumentation: "glass cockpit" and flight data display in external windows
- Visualisation and graphics engine
  - Support for higher-resolution planetary textures
  - Force vector visualisation
- External trajectory data interface
  - Support for simulation replay from Orbiter-recorded or external trajectory data
  - Includes animations and annotations

Topic: Physics engine

Dynamic state integration improved in Orbiter 2006

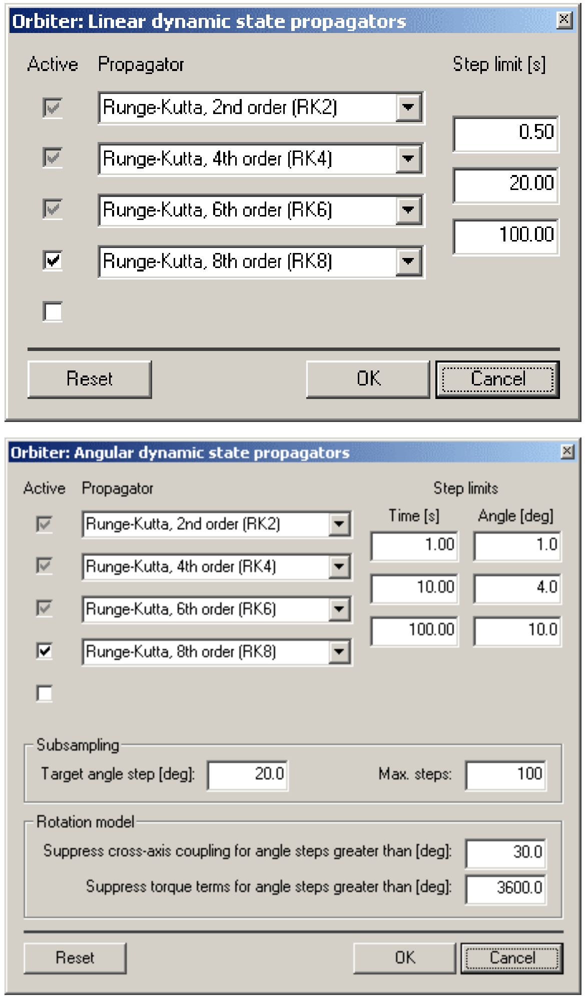
Dynamic state propagation: Integrators

Linear state propagation

- Adaptive steplength-dependent integration order provides accurate dynamic state propagation over a wide range of simulation speeds.
- Available user-definable integrators: *Runge-Kutta* and *symplectic* up to order 8
- Sub-sampling and propagation of perturbations (Encke's method) provide stability at very large time steps.

Angular state propagation

- Integration of Euler's equation of angular motion using RK integrator up to order 8.
- Adaptive and user-definable integration rules and sub-sampling depending on angular velocity



Orbiter linear and angular propagation parameter selection.

Dynamic state propagation: Integrators

Computational complexity of the integrators available in Orbiter.

Runge-Kutta

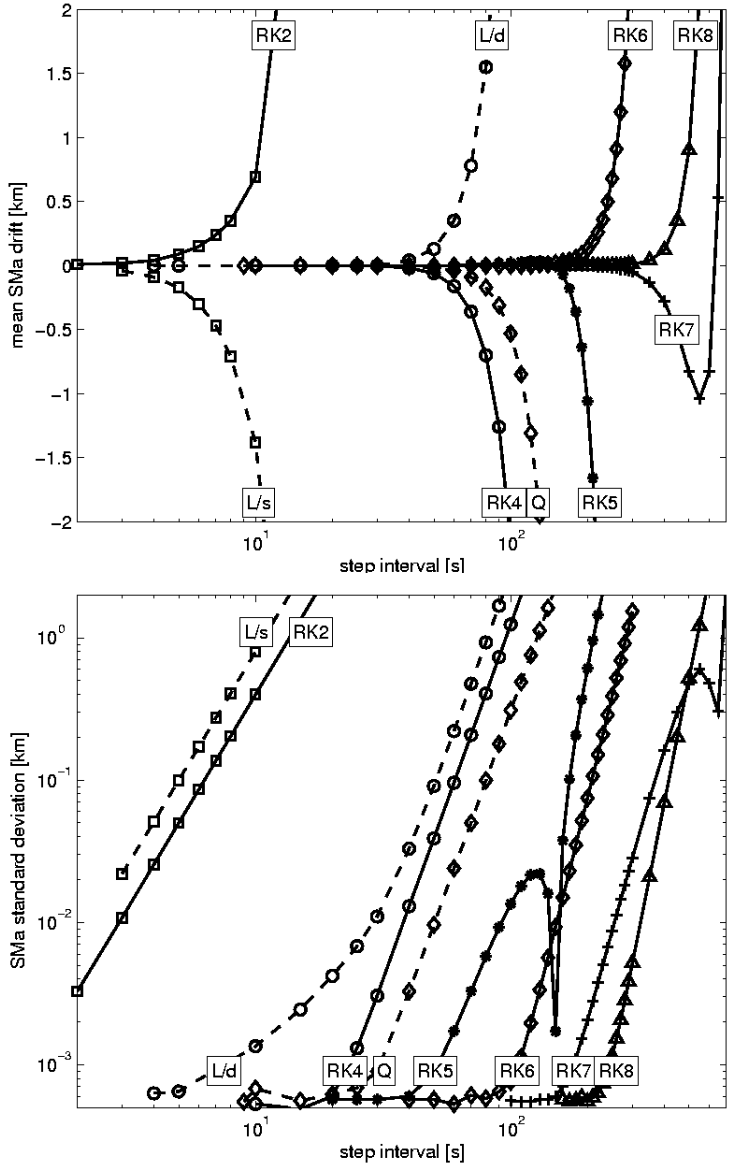
method	stages	timing [µs]
RK2	2	9.7
RK3	3	14.8
RK4	4	16.2
RK5	6	30.5
RK6	8	38.0
RK7	11	49.1
RK8	13	57.8

Symplectic

method	stages	timing [µs]
SY2	2	10.1
SY4	4	20.2
SY6	8	32.3
SY8	16	51.5

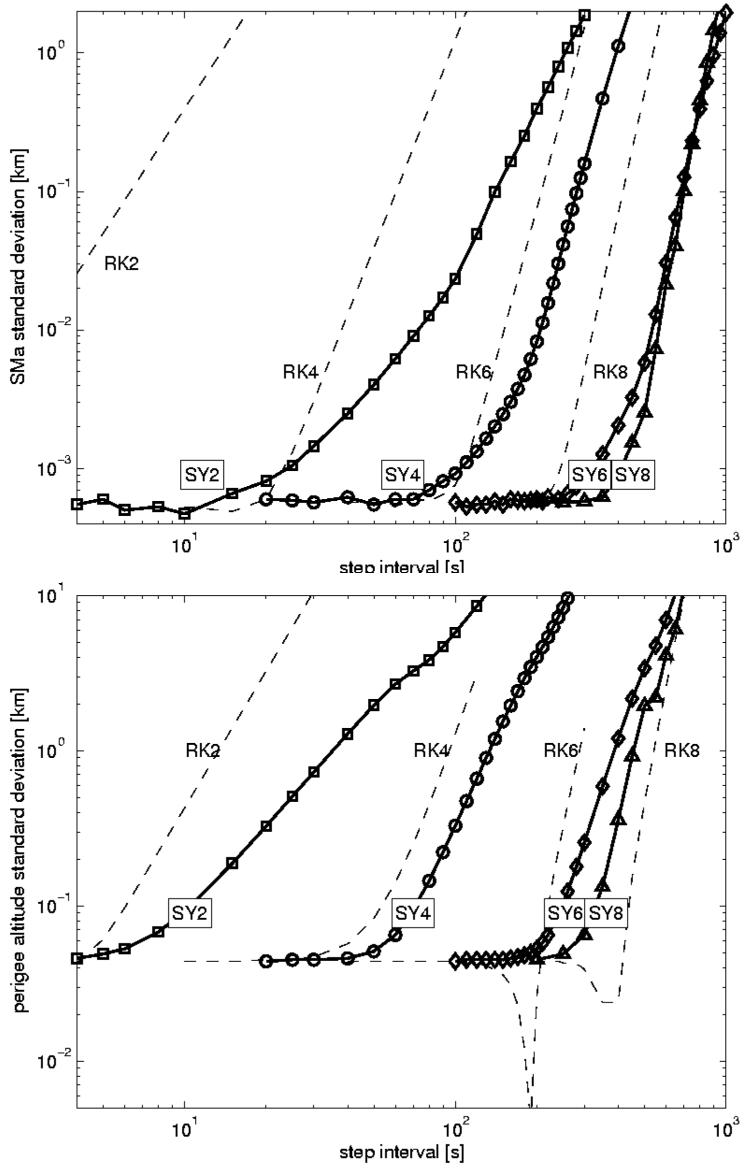
Dynamic state propagation: stability

- Long-term orbit stability with RK integrators
  - Mean drift (top) and standard deviation (bottom) of the semi-major axis for a low Earth orbit (mean altitude 217km) over a period of 10 days, as a function of sampling step length.
  - Shown are different orders of the RK family of integrators available in Orbiter.



Dynamic state propagation: stability

- Comparison between RK and symplectic integrators
  - Standard deviation in semi-major axis (top) and perigee altitude (bottom) of a low Earth orbit over a 10-day period as a function of sampling step length.
  - Shown is the family of symplectic integrators available in Orbiter.
  - For comparison, RK results are shown as dashed lines.



Dynamic state propagation: Perturbations

- Secondary gravity sources
  - Dynamic inclusion of gravity sources from multiple solar system objects (allows e.g. simulation of Lagrange point orbits)

$$U(\mathbf{r}) = \sum_{n}^{N} \frac{GM_n}{|\mathbf{r} - \mathbf{r}_n|} \quad \forall n : \frac{GM_n}{|\mathbf{r} - \mathbf{r}_n|} > U_0$$

Superposition of gravitational potential contributions for given threshold U_0

- Nonspherical gravity sources
  - Spherical harmonics expansion of deformation of planetary gravitational fields due to oblateness
  - allows simulation of propagation of nodes (e.g. sun-synchronous orbits)

$$U(r,\phi) = \frac{GM}{r}\left[1 - \sum_{n=2}^{N} J_n \left(\frac{R}{r}\right)^n P_n(\sin\phi)\right]$$

Perturbations of gravitational potential U, expressed in spherical harmonics with coefficients J_n

- Gravity-gradient torque
  - torque on objects with anisotropic inertia tensors due to inhomogeneous gravitational field
  - allows simulation of resonant oscillations or tidal locking

$$\boldsymbol{\tau}_G = \frac{3GM}{|\mathbf{r}|^3}\left[(\mathbf{L}\hat{\mathbf{r}}) \times \hat{\mathbf{r}}\right]$$

Gravity-gradient induced torque $\boldsymbol{\tau}_G$ at $\mathbf{r}$, given inertia tensor $\mathbf{L}$

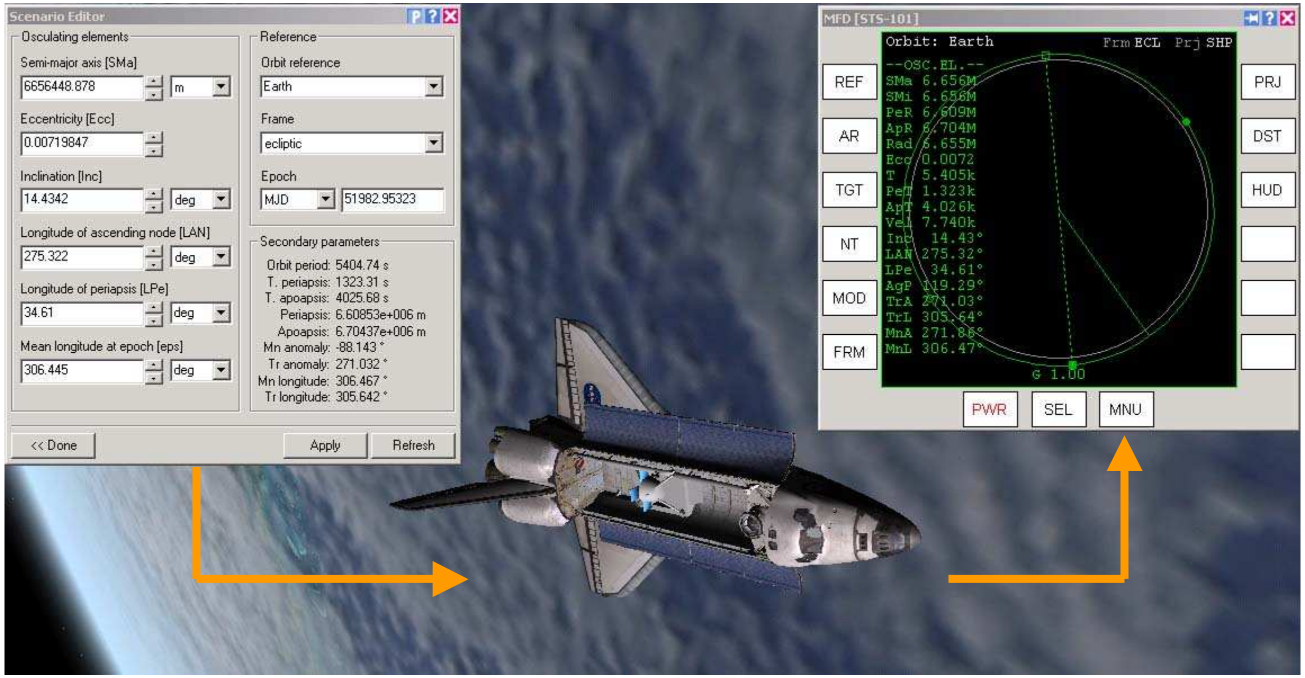
- User-defined perturbations
  - Examples: radiation pressure (orbit perturbation, solar sail simulation, etc.)

Topic: Simulation setup

Scenario editor for interactive spacecraft configuration

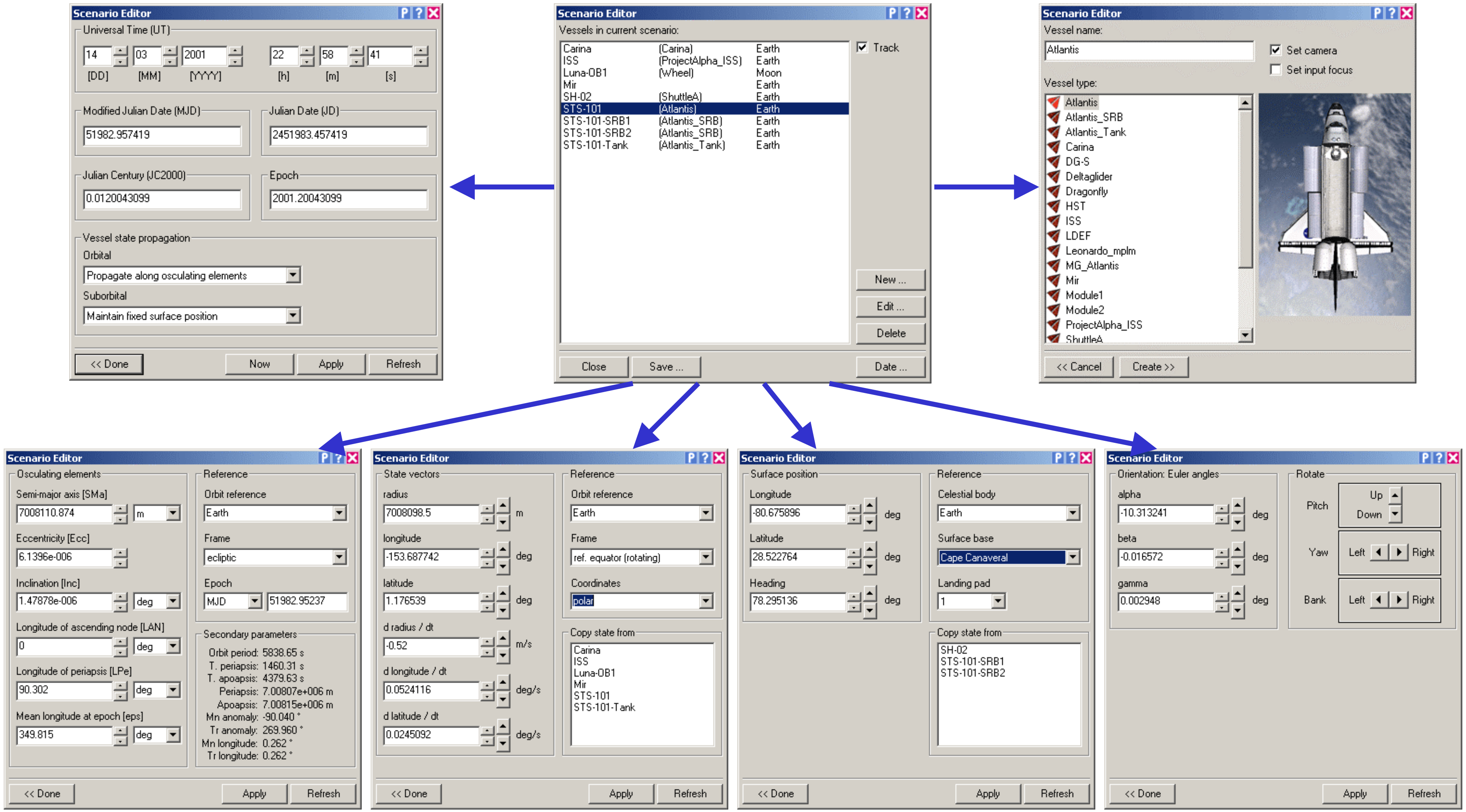
Simulation setup: Scenario editor

- Interactive configuration of spacecraft parameters
  - Orbital elements and state vectors
  - Orientation and angular velocity
  - Surface location
  - Composite structures/docking
  - Propellant status, vessel-specific parameters
  - Simulation date propagation



Simulation setup: Scenario editor

date setup — Scenario inventory — creation



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orbital elements — state vectors — ground location — attitude

Topic: Visualisation

Spacecraft and launch site models: examples

Visualisation examples: Custom launchers

- Launchers and payload can be added to the simulation using custom meshes.
- Engine thrust, ascent behaviour, staging etc. can be defined via plugin modules.
- European launcher examples:
  - Ariane 1

Ariane 1 model by José Manuel García Estévez

Visualisation examples: Custom launchers

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- European launcher examples:
  - Ariane 1
  - Ariane 4

Ariane 4 model by Pierre Refoubelet, Frédéric Servian, Christophe Etienne, Stéphane Colombain

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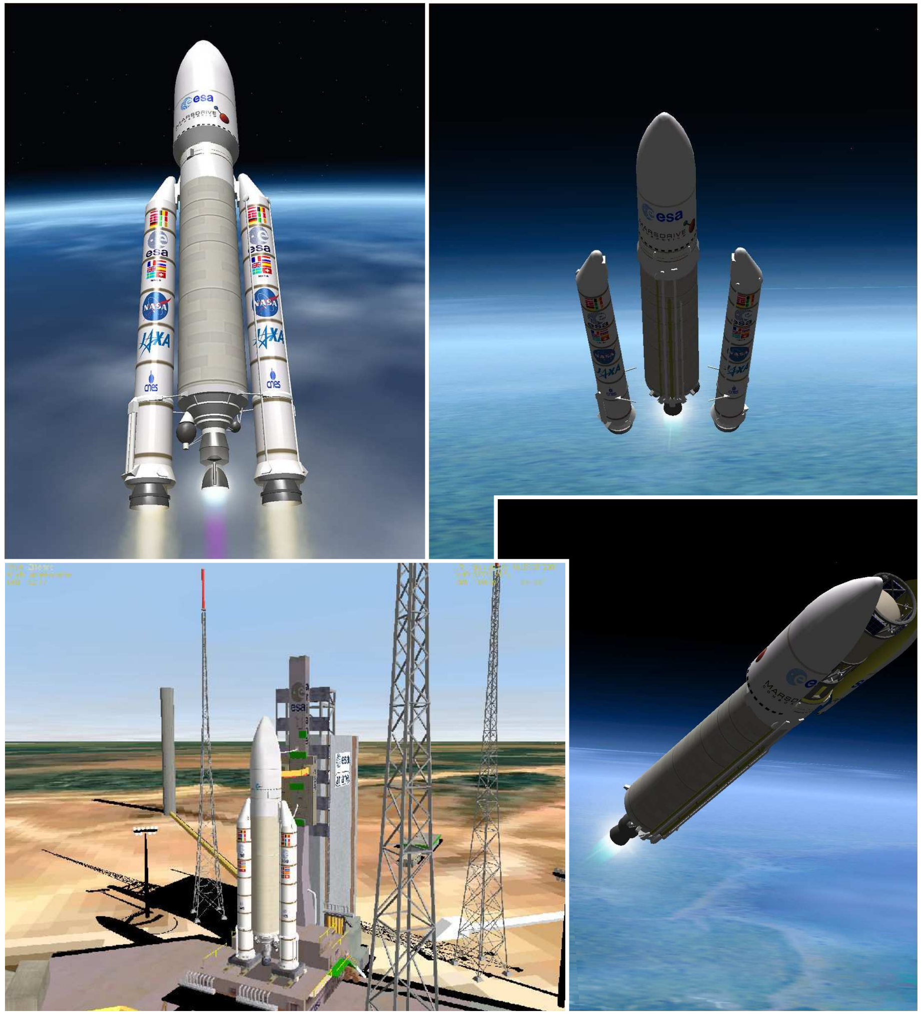
  - Ariane 4
  - Ariane 5



Ariane 5 model by Thomas Ruth, with modifications by Andy McSorley

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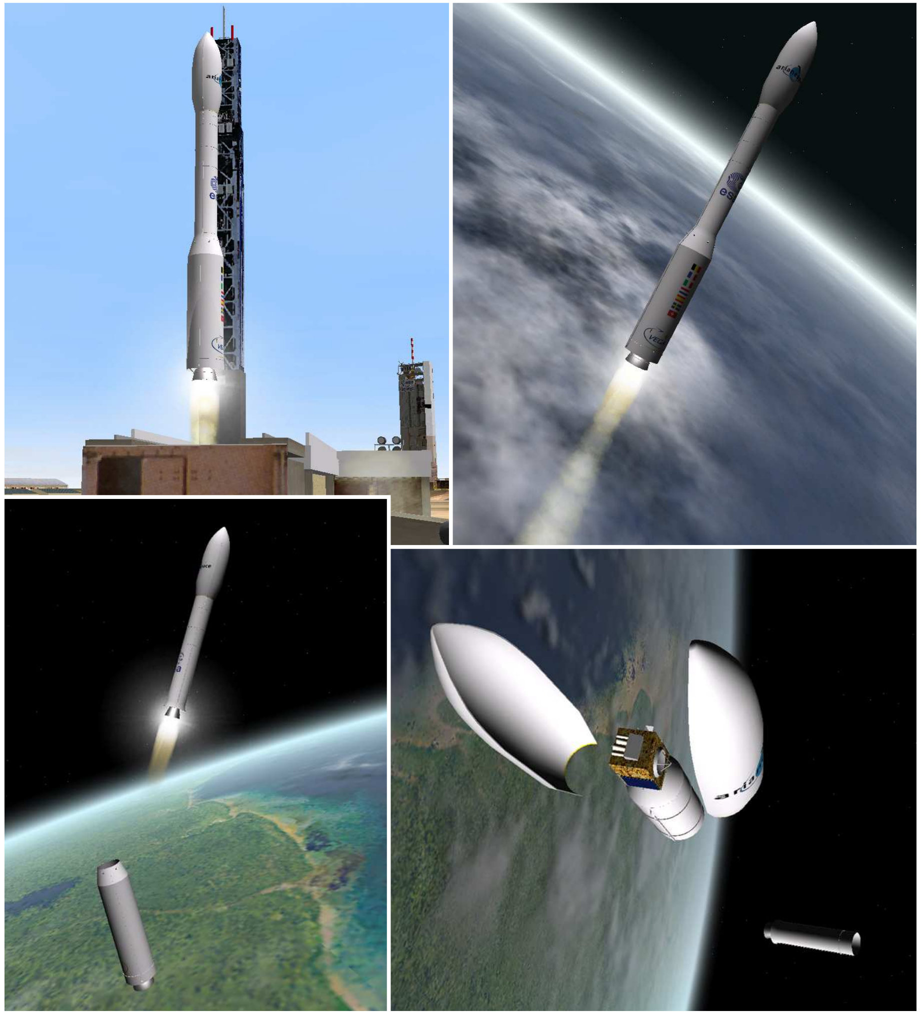
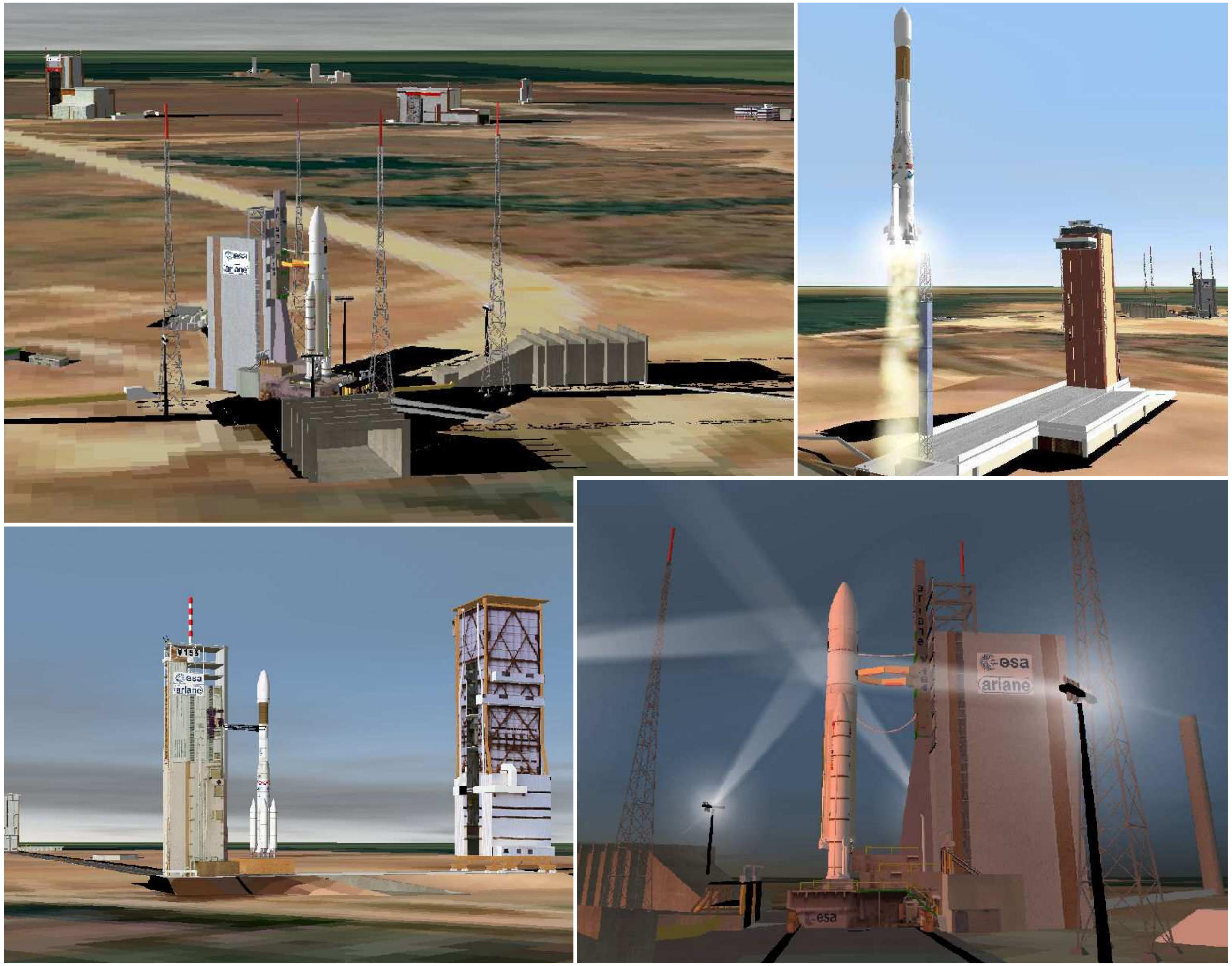
  - Ariane 5
  - VEGA



Vega model by José Manuel García Estévez

Visualisation examples: Ground structures

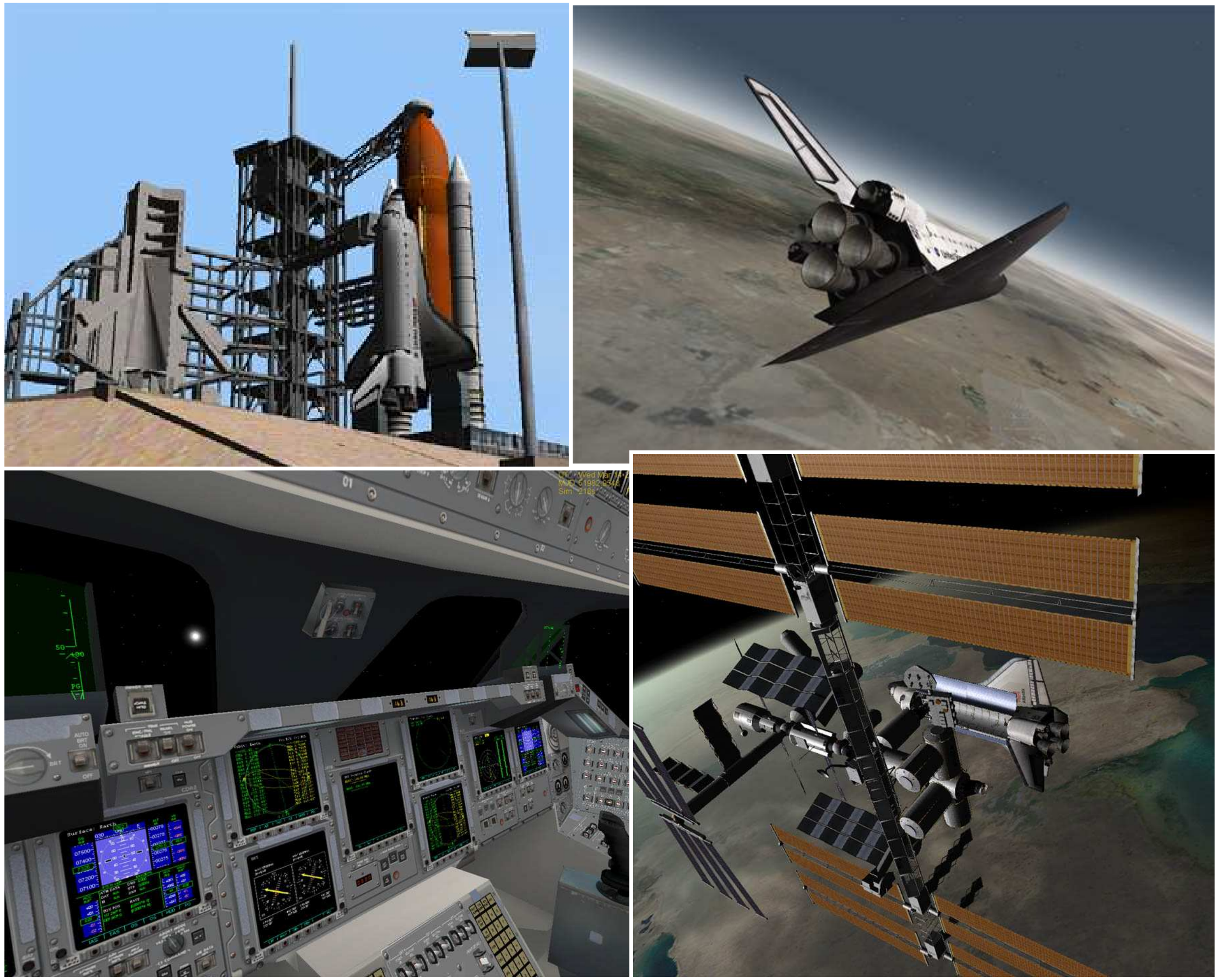
- Custom ground structures for launch sites can be added to the simulation.
- Example: Kourou
  - ELA1
  - ELA2
  - ELA3



Kourou site by Pierre Refoubelet, Frédéric Servian, Christophe Etienne, Stéphane Colombain

Visualisation examples: Space Shuttle

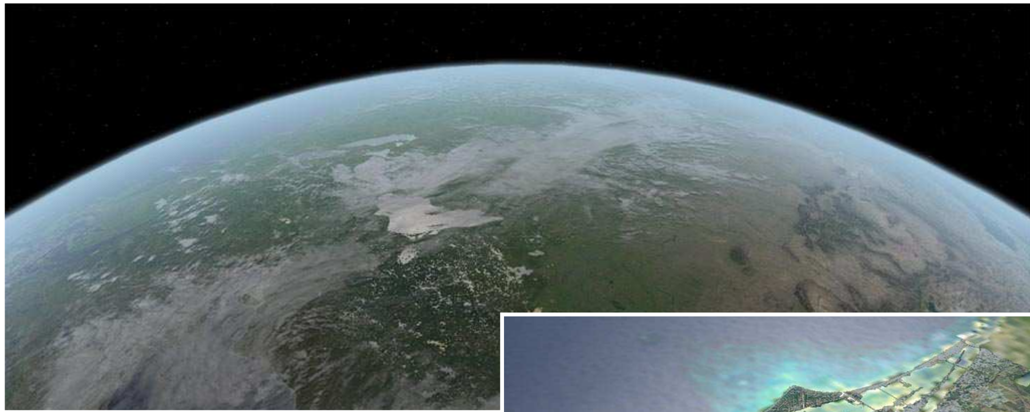
- Manned spacecraft: Modelling of flight deck interior ("virtual cockpit")
- Interactive manipulation of flight controls/ instrumentation
- Example:
  - Space Shuttle Atlantis

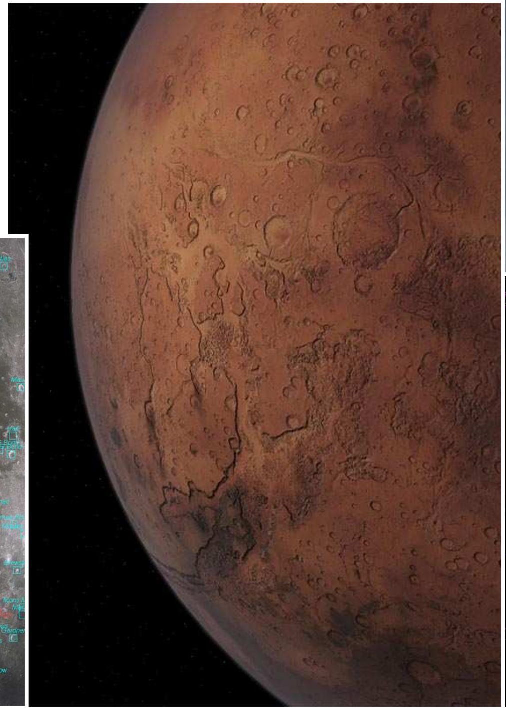


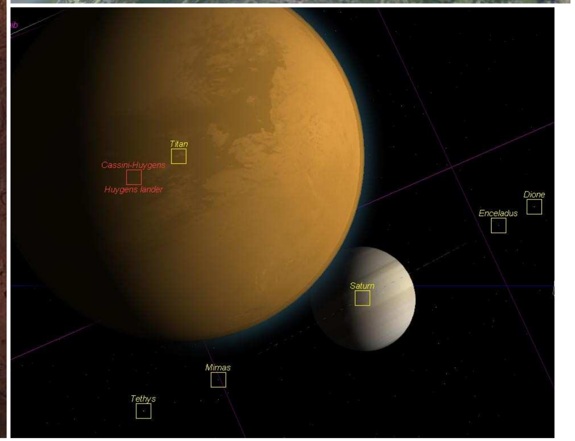
Atlantis model by Michael Grosberg, with extensions by Don Gallagher

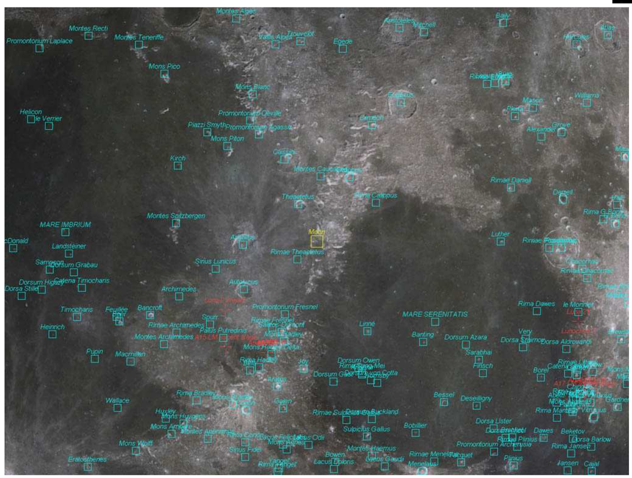
Visualisation examples: Planetary surfaces

- Celestial body surfaces:
- adaptive resolution as a function of apparent size up to 32k x 16k (equiv. 1.2km for Earth)
- support for local high-resolution textures (e.g. launch sites)
- support for specular reflections from water surfaces, cloud layers, atmospheric haze and city lights.
- support for celestial and surface labels and markers







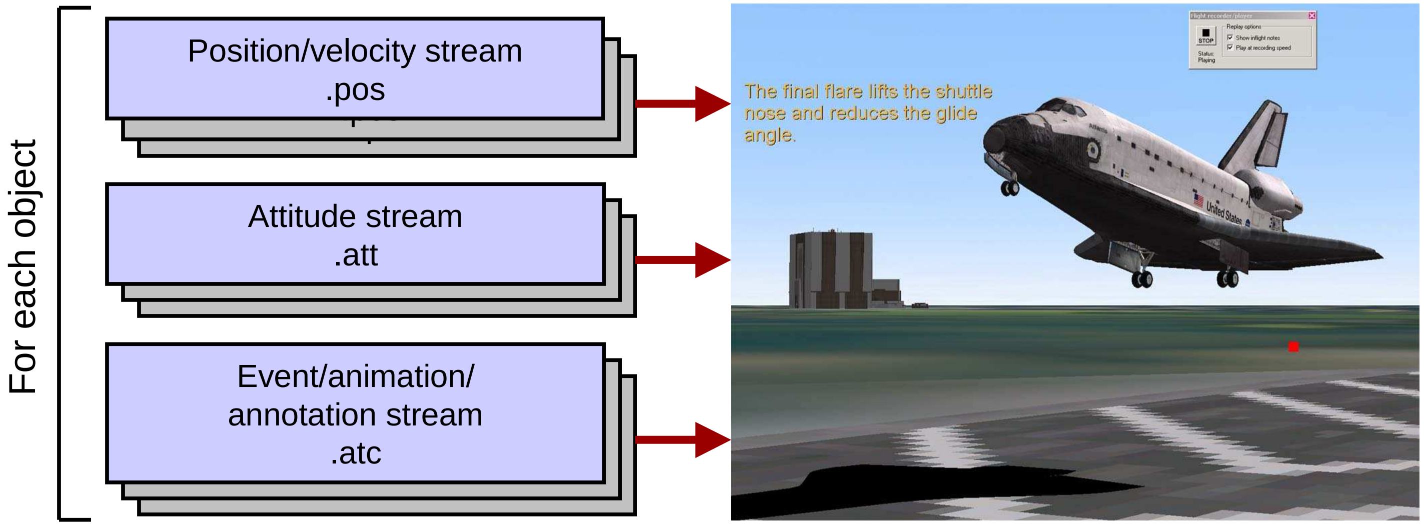


Topic: Flight recording and playback

Visualisation of externally provided trajectory data

Playback from external trajectory data

- **Data format**
  - Sampled position and velocity data (ecliptic or equatorial reference)
  - Sampled attitude data (ecliptic or local horizon reference)
  - Articulation data (engine and animation events, staging, booster separation, onscreen annotations, playback speed, etc.)



- **Replay mode**
  - Mixture of playback-controlled and active spacecraft is possible
  - User- or datastream-controlled playback speed
  - User-controlled camera

Playback from external trajectory data

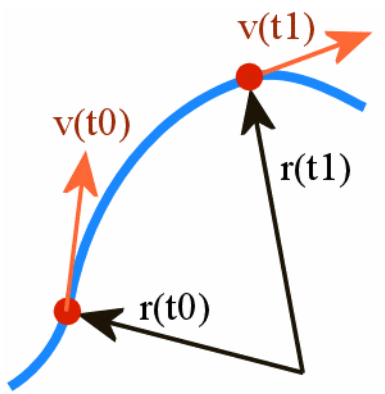
- Data interpolation
  - C2-continuous interpolation: piecewise linear acceleration
  - Given state samples $r_0=r(t_0)$, $r_1=r(t_1)$ and $v_0=v(t_0)$, $v_1=v(t_1)$ at consecutive sampling times t_0, t_1, the acceleration satisfies

$$a(t) = a_0 + b\Delta t, \quad t_0 \le t \le t_1, \quad \Delta t = t - t_0$$

  - Equations of motion: Integration of state vectors leads to

$$v(t) = \int_0^{\Delta t} a(t')dt' = v_0 + a_0\Delta t + \frac{1}{2}b\Delta t^2$$

$$r(t) = \int_0^{\Delta t} v(t')dt' = r_0 + v_0\Delta t + \frac{1}{2}a_0\Delta t^2 + \frac{1}{6}b\Delta t^3$$

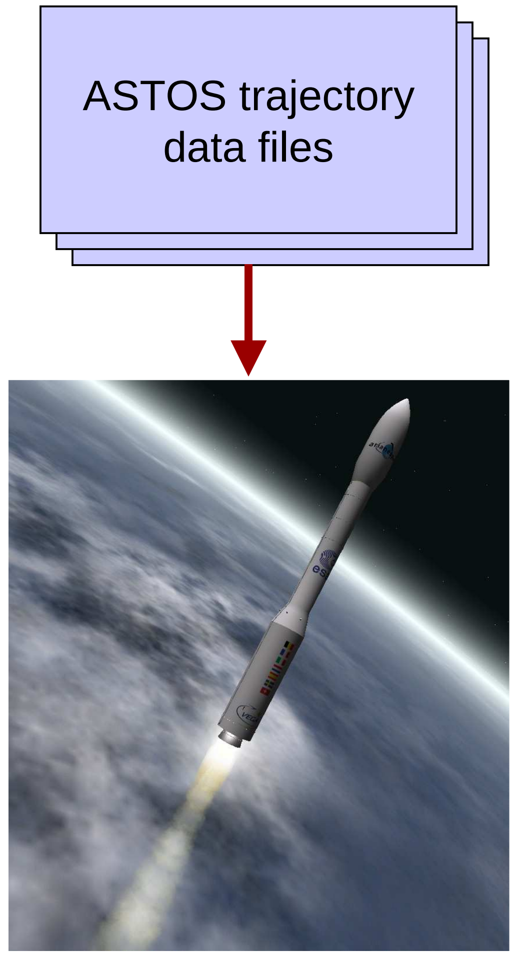


  - resulting in parameters

$$\left.\begin{aligned} a_0 &= \frac{2[3(r_1 - r_0) - \Delta T(2v_0 + v_1)]}{\Delta T^2} \\ b &= \frac{6[2(r_0 - r_1) + \Delta T(v_0 + v_1)]}{\Delta T^3} \end{aligned}\right\} \quad \Delta T = t_1 - t_0$$

Playback from external trajectory data

- Example: Interface to ASTOS trajectory data
  - The Orbiter playback interface was designed to accept data from the ASTOS aerospace trajectory optimisation software.
  - The ASTOS position/velocity and attitude data samples can be used as playback input streams for Orbiter.
  - Additional spacecraft-specific events (stageing, animations) and onscreen annotations can be added via the articulation stream to create complete launch demonstrations.
  - This allows to use Orbiter as a visualisation tool or demonstrator for ASTOS trajectory data.
  - Example: VEGA launch vehicle: launch, orbital insertion and payload deployment.



Summary

- Orbiter is a modular customisable real-time simulation and visualisation tool for spacecraft operation.
- Programming interface supports data exchange between Orbiter core and 3rd party addon modules.
- Versatile: simulation of historic missions or hypothetical concepts; "virtual prototyping"
- Built-in physics engine: dynamic propagation of linear and angular state vectors over a wide range of sampling intervals, including various perturbation sources.
- User interface: fast setup of spacecraft parameters via scenario editor; real-time simulation of flight instrumentation, immersive simulation of manned missions: "virtual cockpits".
- Support for mission playback from recorded or externally provided trajectory data, for demonstration and visualisation.

Resources and acknowledgements

- Orbiter main site and addon repositories:
  - orbit.medphys.ucl.ac.uk (Orbiter main site and core download)
  - www.orbithangar.com (Orbiter addon repository)
  - www.avsim.com (includes Orbiter addon repository)
  - users.swing.be/vinka (spacecraft wrapper dll for rapid prototyping)
- Educational resources:
  - "Go Play In Space" e-book by Bruce Irving, available at: www.orbiter.migman.com/orbiter.htm
  - Resources for educators, maintained by Jean-Marc Perreault: www.orbiterschool.com

I would like to thank the following authors for contributing addon models to Orbiter presented here:

Pierre Refoubelet, Frédéric Servian, Christophe Etienne, Stéphane Colombain (Ariane 1+4 models and Kourou site)

Thomas Ruth and Andy McSorley (Ariane 5 model)

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