

Spacecraft Simulation and Visualisation with Orbiter 2006

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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

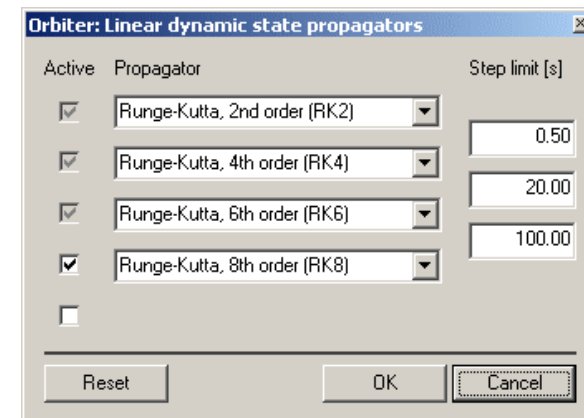
Dynamic state propagation: Integrators

■ 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

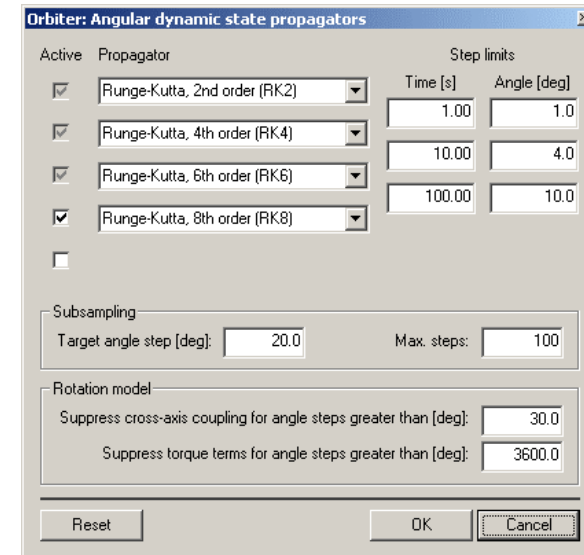
- Integration of Euler's equation of angular motion using RK integrator up to order 8.
- Adaptive and user-definable integration rules and sub-sampling depending on angular velocity



Orbiter: Linear dynamic state propagators

Active	Propagator	Step limit [s]
<input checked="" type="checkbox"/>	Runge-Kutta, 2nd order (RK2)	0.50
<input checked="" type="checkbox"/>	Runge-Kutta, 4th order (RK4)	20.00
<input checked="" type="checkbox"/>	Runge-Kutta, 6th order (RK6)	100.00
<input checked="" type="checkbox"/>	Runge-Kutta, 8th order (RK8)	
<input type="checkbox"/>		

Buttons: Reset, OK, Cancel



Orbiter: Angular dynamic state propagators

Active	Propagator	Time [s]	Angle [deg]
<input checked="" type="checkbox"/>	Runge-Kutta, 2nd order (RK2)	1.00	1.0
<input checked="" type="checkbox"/>	Runge-Kutta, 4th order (RK4)	10.00	4.0
<input checked="" type="checkbox"/>	Runge-Kutta, 6th order (RK6)	100.00	10.0
<input checked="" type="checkbox"/>	Runge-Kutta, 8th order (RK8)		
<input type="checkbox"/>			

Subsampling: Target angle step [deg]: 20.0, Max. steps: 100

Rotation model: Suppress cross-axis coupling for angle steps greater than [deg]: 30.0, Suppress torque terms for angle steps greater than [deg]: 3600.0

Buttons: Reset, OK, Cancel

Orbiter linear and angular propagation parameter selection.

Dynamic state propagation: Integrators

Computational complexity of the integrators available in Orbiter.

Runge-Kutta

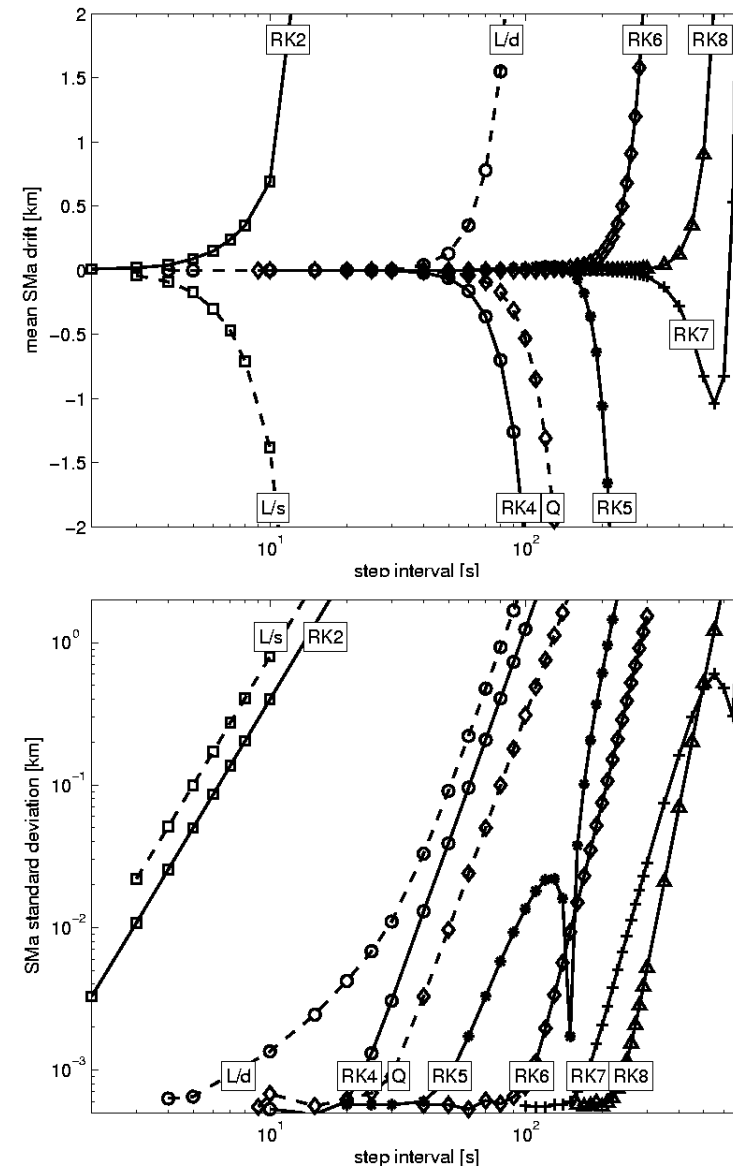
method	stages	timing [μ s]
RK2	2	9.7
RK3	3	14.8
RK4	4	16.2
RK5	6	30.5
RK6	8	38.0
RK7	11	49.1
RK8	13	57.8

Symplectic

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

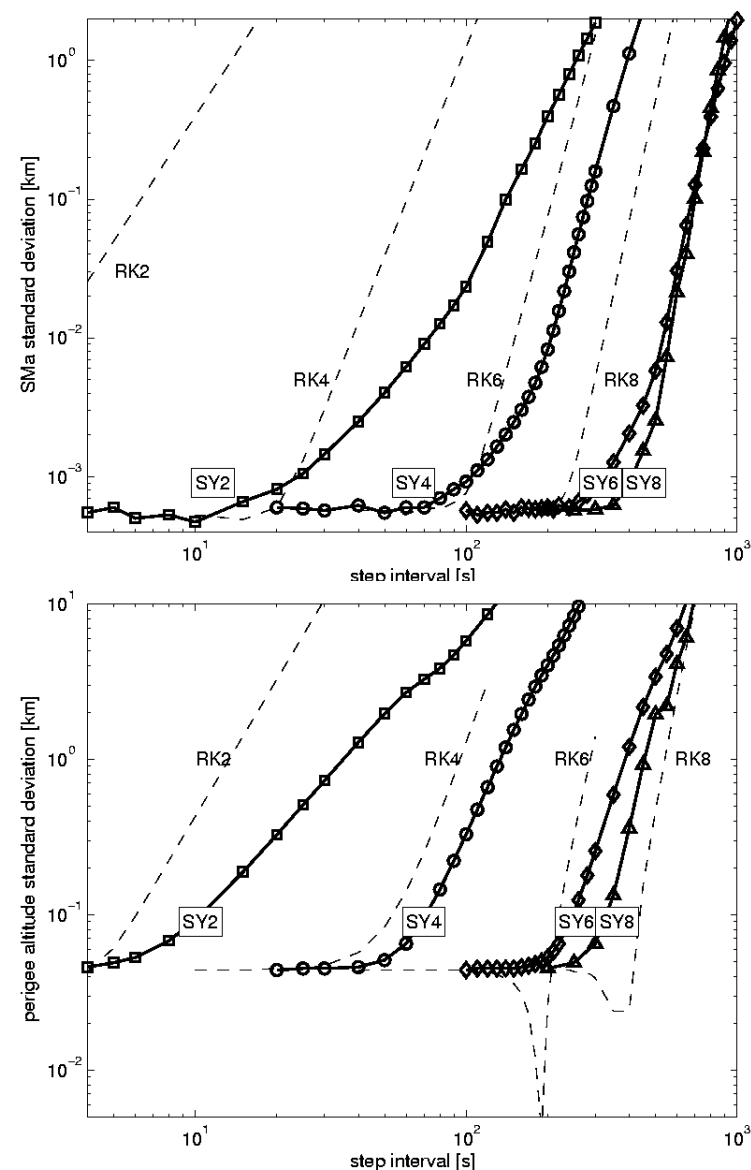
Dynamic state propagation: stability

- 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

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

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.)

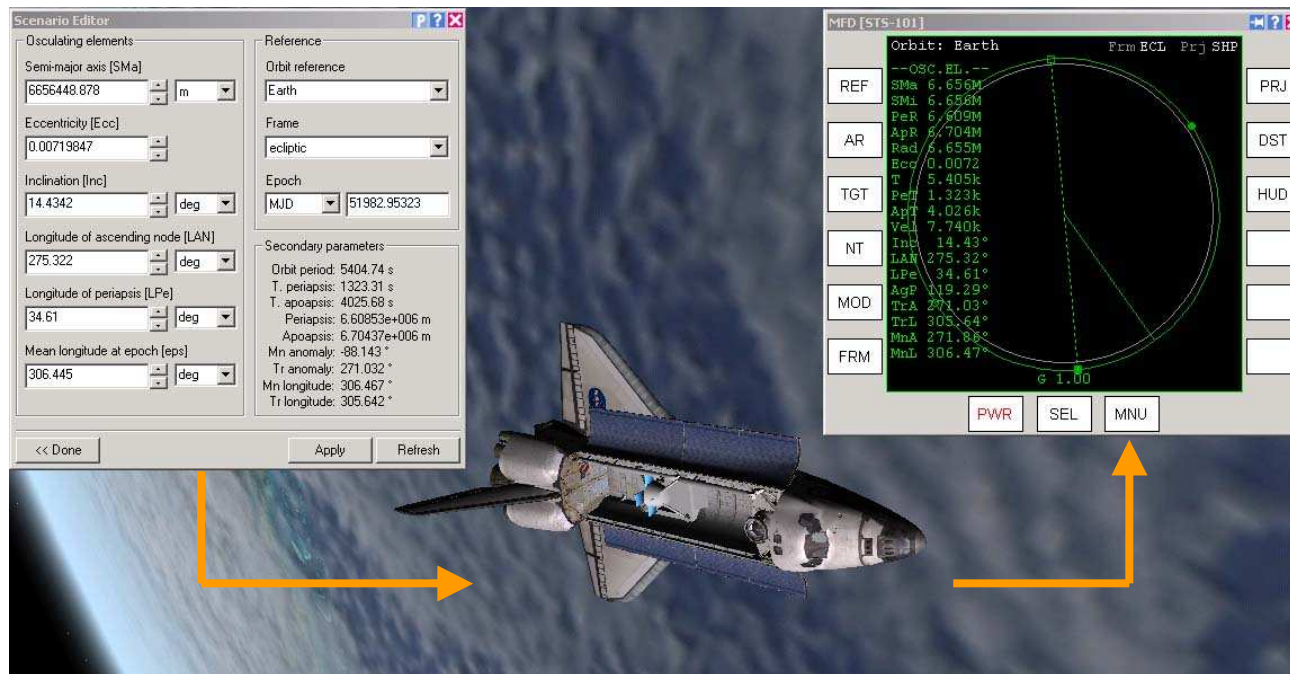
Topic: Simulation setup

Scenario editor for interactive spacecraft configuration

Simulation setup: Scenario editor

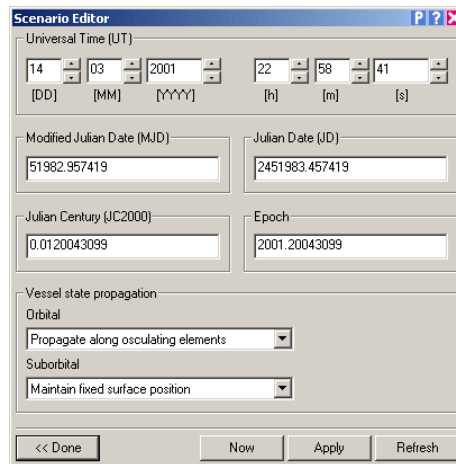
■ Interactive configuration of spacecraft parameters

- 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 Editor

Universal Time (UT)

14 03 2001 22 58 41
[DD] [MM] [YYYY] [h] [m] [s]

Modified Julian Date (MJD)
51982.957419

Julian Date (JD)
2451983.457419

Julian Century (JC2000)
0.0120043099

Epoch
2001.20043099

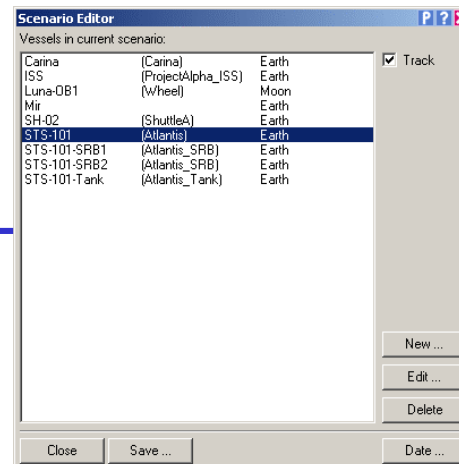
Vessel state propagation

Orbital
Propagate along osculating elements

Suborbital
Maintain fixed surface position

<< Done Now Apply Refresh

Scenario inventory



Scenario Editor

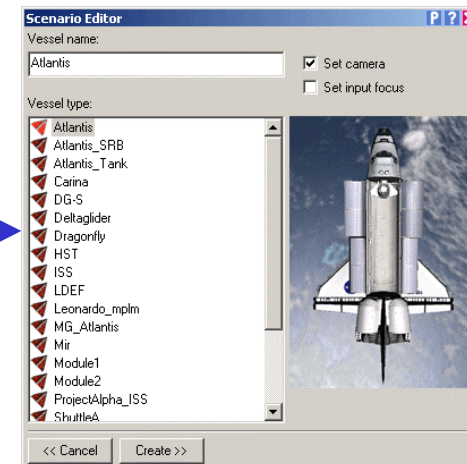
Vessels in current scenario:

Carina	(Carina)	Earth	<input checked="" type="checkbox"/> Track
ISS	(ProjectAlpha_ISS)	Earth	
Luna-DB1	(Wheel)	Moon	
Mir	(ShuttleA)	Earth	
SH-02	(ShuttleA)	Earth	
STS-101	(Atlantis)	Earth	
STS-101-SRB1	(Atlantis_SRB)	Earth	
STS-101-SRB2	(Atlantis_SRB)	Earth	
STS-101-Tank	(Atlantis_Tank)	Earth	

New ... Edit ... Delete

Close Save ... Date ...

creation



Scenario Editor

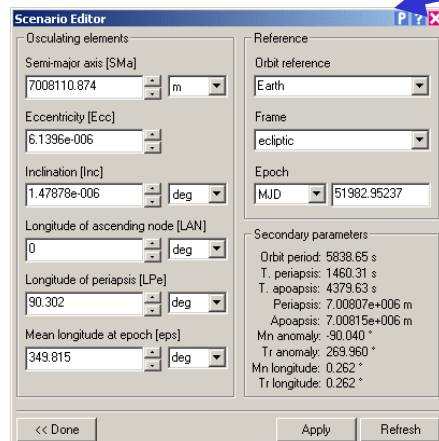
Vessel name:
Atlantis

☒ Set camera
☐ Set input focus

Vessel type:

- Atlantis
- Atlantis_SRB
- Atlantis_Tank
- Carina
- DG-S
- Deltaglider
- Dragonfly
- HST
- ISS
- LDEF
- Leonardo_mplm
- MG_Atlantis
- Mir
- Module1
- Module2
- ProjectAlpha_ISS
- ShuttleA

<< Cancel Create >>



Scenario Editor

Osculating elements

Semi-major axis [SMA]
7008110.874 m

Eccentricity [Ecc]
6.1396e-006

Inclination [Inc]
1.47879e-006 deg

Longitude of ascending node [LAN]
0 deg

Longitude of periaapsis [LPe]
90.302 deg

Mean longitude at epoch [eps]
349.815 deg

Reference

Orbit reference
Earth

Frame
ecliptic

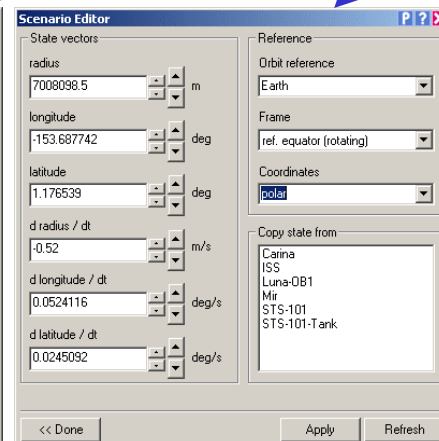
Epoch
MJD 51982.95237

Secondary parameters

Orbit period: 5838.65 s
T. periaapsis: 1460.31 s
T. apoapsis: 4379.63 s
Periaapsis: 7.00807e+006 m
Apoapsis: 7.00815e+006 m
Mn anomaly: -90.040 °
Tr anomaly: 269.960 °
Mn longitude: 0.262 °
Tr longitude: 0.262 °

<< Done Apply Refresh

orbital elements



Scenario Editor

State vectors

radius
7008098.5 m

longitude
-153.687742 deg

latitude
1.176539 deg

d radius / dt
-0.52 m/s

d longitude / dt
0.0524116 deg/s

d latitude / dt
0.0245092 deg/s

Reference

Orbit reference
Earth

Frame
ref. equator (rotating)

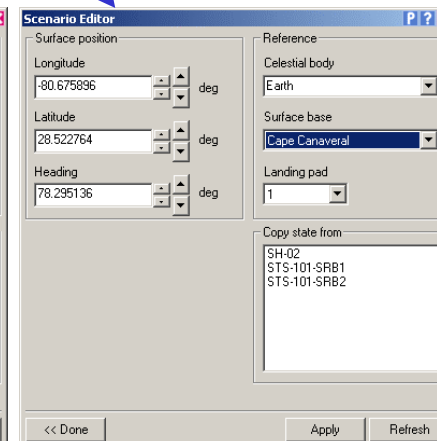
Coordinates
polar

Copy state from

Carina
ISS
Luna-DB1
Mir
STS-101
STS-101-Tank

<< Done Apply Refresh

state vectors



Scenario Editor

Surface position

Longitude
-80.675896 deg

Latitude
28.522764 deg

Heading
78.295136 deg

Reference

Celestial body
Earth

Surface base
Cape Canaveral

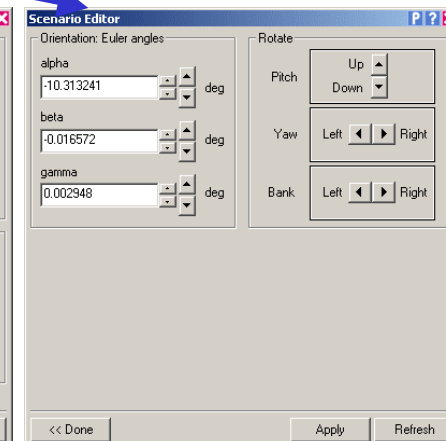
Landing pad
1

Copy state from

SH-02
STS-101-SRB1
STS-101-SRB2

<< Done Apply Refresh

ground location



Scenario Editor

Orientation: Euler angles

alpha
-10.313241 deg

beta
-0.016572 deg

gamma
0.002948 deg

Rotate

Pitch
Up
Down

Yaw
Left
Right

Bank
Left
Right

<< Done Apply Refresh

attitude

Topic: Visualisation

Spacecraft and launch site models: examples

Visualisation examples: Custom launchers

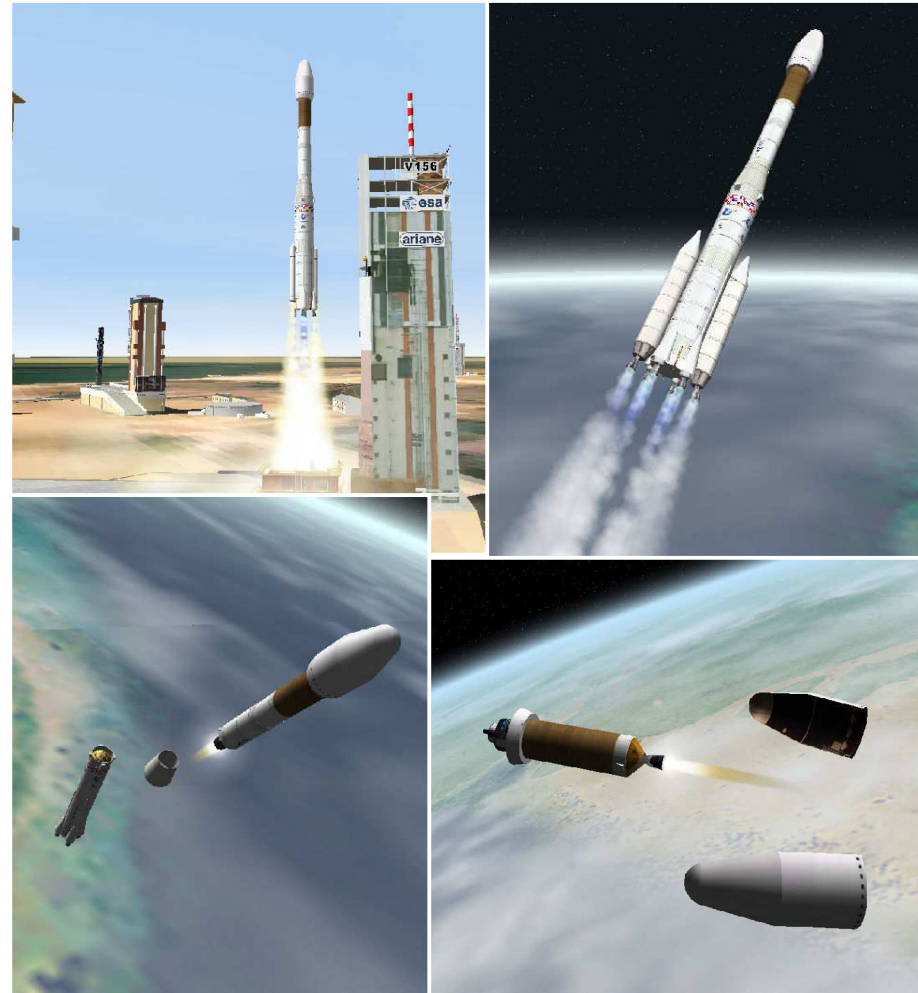
- Launchers and payload can be added to the simulation using custom meshes.
- Engine thrust, ascent behaviour, staging etc. can be defined via plugin modules.
- European launcher examples:
 - Ariane 1



Ariane 1 model by José Manuel García Estévez

Visualisation examples: Custom launchers

- 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 4



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

Visualisation examples: Custom launchers

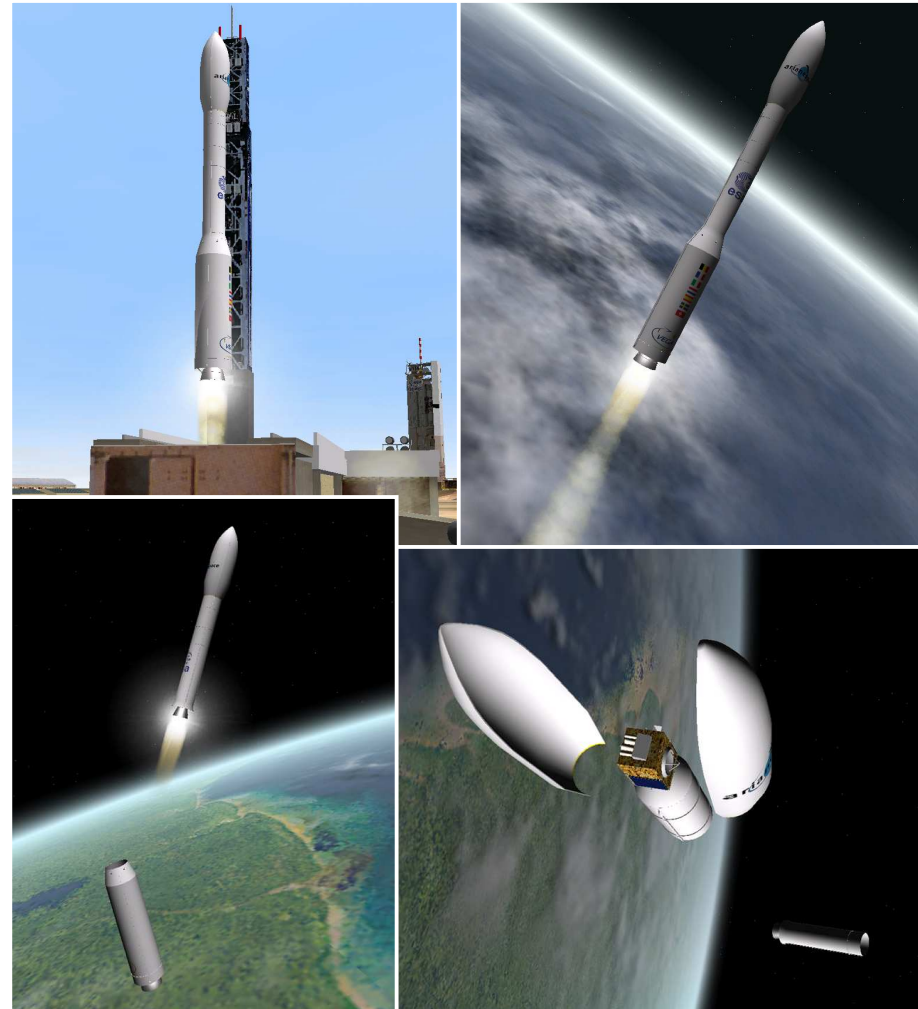
- Launchers and payload can be added to the simulation using custom meshes.
- Engine thrust, ascent behaviour, staging etc. can be defined via plugin modules.
- European launcher examples:
 - Ariane 1
 - Ariane 4
 - **Ariane 5**



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

Visualisation examples: Custom launchers

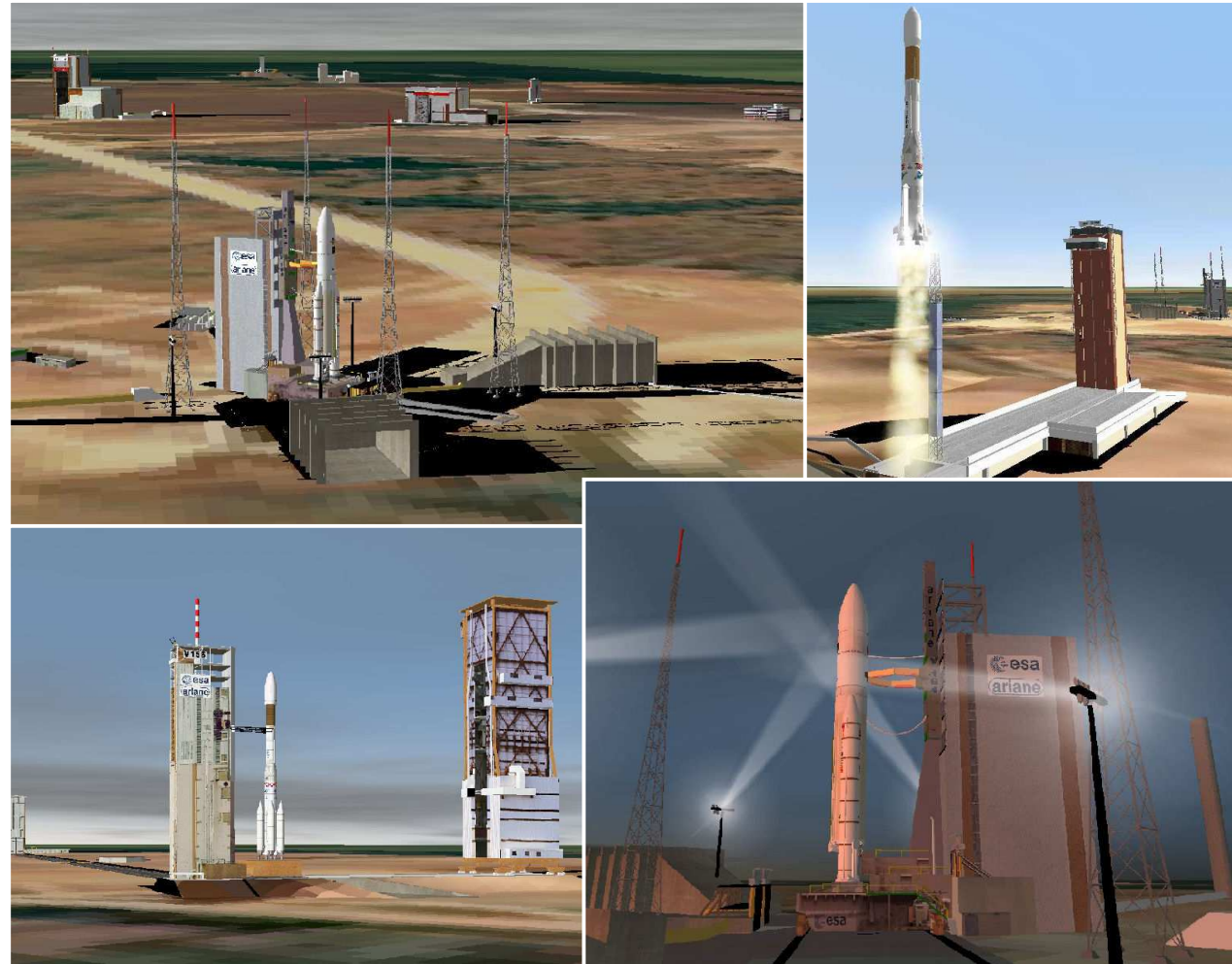
- Launchers and payload can be added to the simulation using custom meshes.
- Engine thrust, ascent behaviour, staging etc. can be defined via plugin modules.
- European launcher examples:
 - Ariane 1
 - Ariane 4
 - Ariane 5
 - **VEGA**



Vega model by José Manuel García Estévez

Visualisation examples: Ground structures

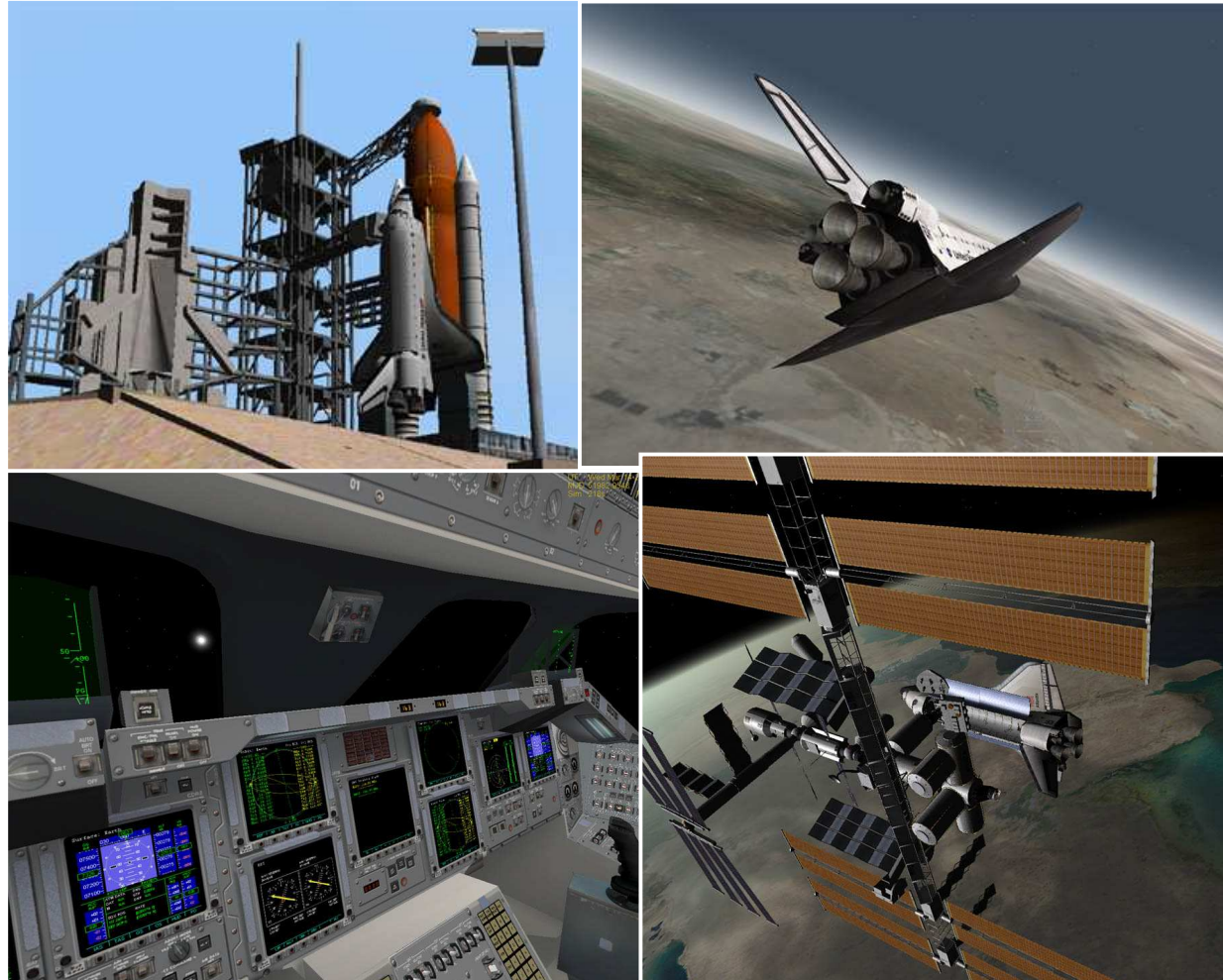
- Custom ground structures for launch sites can be added to the simulation.
- Example: Kourou
 - ELA1
 - ELA2
 - ELA3



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

Visualisation examples: Space Shuttle

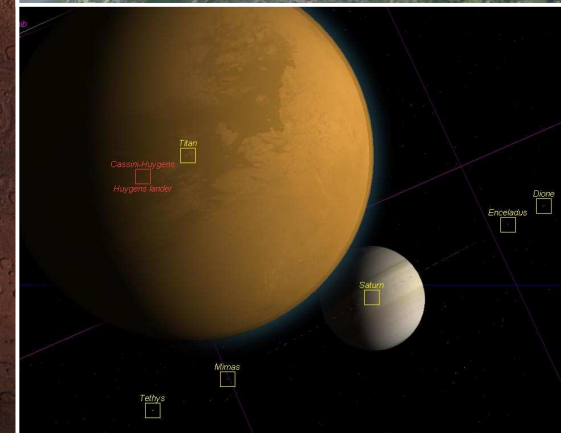
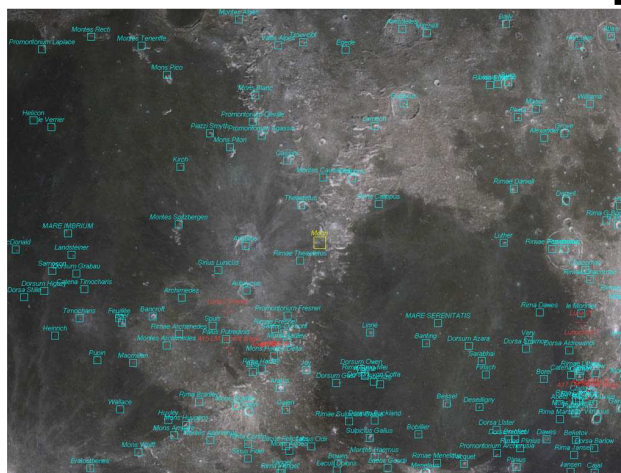
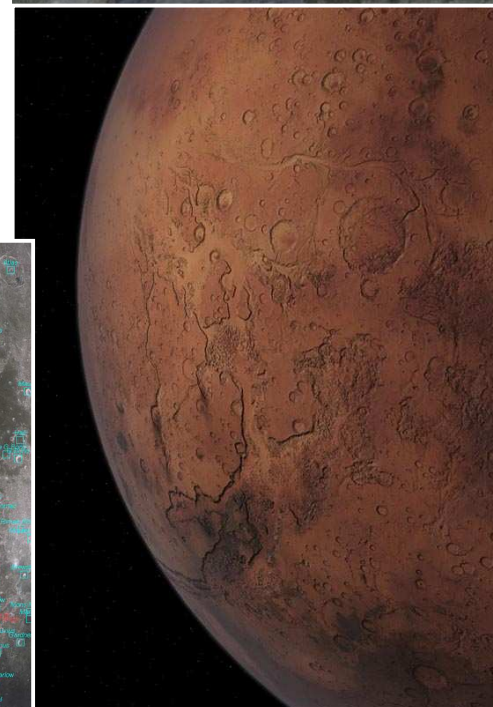
- Manned spacecraft:
Modelling of flight deck interior ("virtual cockpit")
- Interactive manipulation of flight controls/instrumentation
- Example:
 - Space Shuttle Atlantis



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



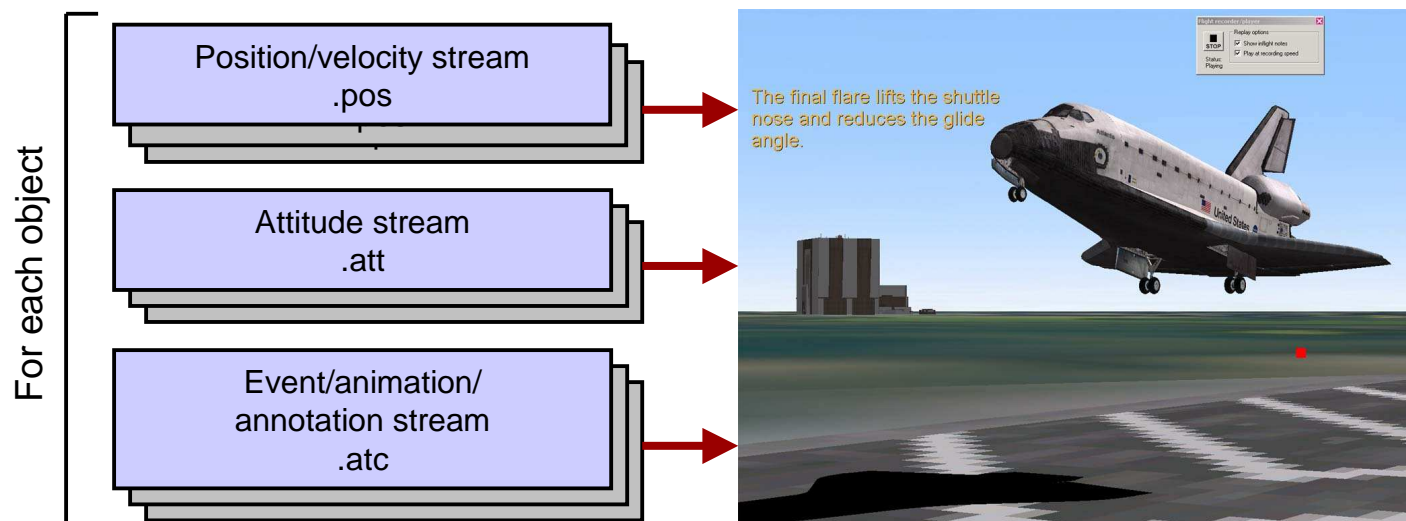
Topic: Flight recording and playback

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

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

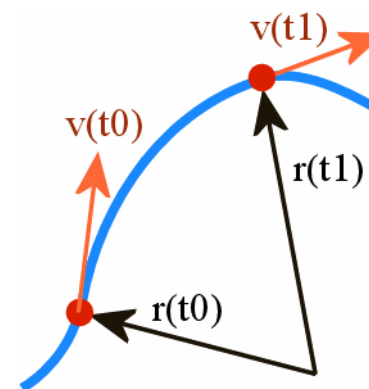
- Equations of motion: Integration of state vectors leads to

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

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

- resulting in parameters

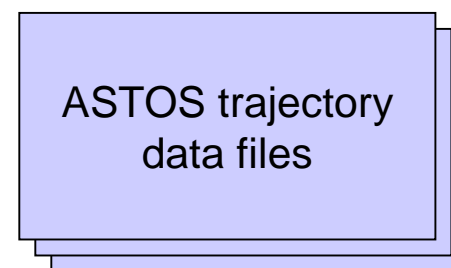
$$\left. \begin{aligned} a_0 &= \frac{2[3(r_1 - r_0) - \Delta T(2v_0 + v_1)]}{\Delta T^2} \\ b &= \frac{6[2(r_0 - r_1) + \Delta T(v_0 + v_1)]}{\Delta T^3} \end{aligned} \right\} \Delta T = t_1 - t_0$$



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)

José Manuel García Estévez, supported by Hispaseti.org and Astoseti.org (Vega model)

Michael Grosberg and Don Gallagher (Atlantis model)

Seth Hollingsead, Rolf Keibel and others (planetary textures)

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