# Orbiter:
# A Free Spacecraft Simulation Tool

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## Overview

- Orbiter is a real-time space flight simulation for Windows PC platforms.
- Modelling of atmospheric flight (launch and reentry), suborbital, orbital and interplanetary missions (rendezvous, docking, transfer, swing-by etc.)
- Newtonian mechanics, rigid body model of rotation, basic atmospheric flight model.
- Planet positions from public perturbation solutions. Time integration of state vectors or osculating elements.
- Developed since 2000 as an educational and recreational application for orbital mechanics simulation.
- Written in C++, using DirectX for 3-D rendering. Public programming interface for development of external module plugins.
- With an increasingly versatile API, development focus is beginning to shift from the Orbiter core to 3rd party addons.

## Scope

- Launch sequence from surface to orbital insertion (including atmospheric effects: drag, pressure-dependent engine ISP ...)
- Orbital manoeuvres (alignment of orbital plane, orbit-to-orbit transfers, rendezvous)
- Vessel-to-vessel approach and docking. Building of superstructures from vessel modules (including simple rules for updating the rigid-body model).
- Release and re-capture of satellites.
- Re-entry.
- Interplanetary transfers (including Hohmann orbits, slingshot manoeuvres)
- Atmospheric flight (aerodynamic flight model, airfoil definition, runway takeoff/landing, airbreathing engines)

## Limitations

- Stability of time propagation: step length is defined frame update (variable step size, shared resources with graphics updates)
- Flight model: no native support yet for radiation pressure, micro-drag at high altitude. Simple rigid-body model (no native support for tethers, internal mass distribution changes ...)
- Simple atmospheric flight model
- No collision detection
- No damage modelling
- No native multi-user support

## Time propagation

Real-time simulation with time acceleration up to $10^4$ and variable step length determined by processor speed, graphics load, simulation complexity etc.

Method 1:
Semi-analytic perturbation solutions for celestial bodies (VSOP87, ELP2000 ...)

Method 2:
Propagation of state vectors $\mathbf{r}(t_i) \rightarrow \mathbf{r}(t_{i+1})$, $\mathbf{v}(t_i) \rightarrow \mathbf{v}(t_{i+1})$ with $4^{th}$ order Runge-Kutta.

Method 3:
Updating elements of osculating orbit from perturbations of the primary gravitational field.

# Gravity calculation

Orbiter accomodates perturbations of the radial symmetry of gravitational potential sources in a single (polar) dimension using a harmonic series:

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

with Legendre polynomial $P_n$ of order $n$, and perturbation coefficients $J_n$. Number of terms $N$ is adjusted automatically as a function of distance $r$.

| | | |
|---|---|---|
| Earth | $J_2 = 1082.63$ | x $10^{-6}$ |
| | $J_3 = -2.51$ | |
| | $J_4 = -1.6$ | |
| | $J_5 = 0.13$ | |
| Mercury | $J_2 = 60$ | |
| Venus | $J_2 = 27$ | |
| Mars | $J_2 = 1964$ | |
| Jupiter | $J_2 = 14750$ | |
| Saturn | $J_2 = 16450$ | |
| Uranus | $J_2 = 12000$ | |
| Neptune | $J_2 = 4000$ | |

A full spherical harmonics expansion of the field perturbations in both polar ($\phi$) and azimuth direction ($\lambda$) is planned for a future version.

# Rigid-body model and composite structures

Orbiter uses a simplified model of rigid body motion to construct superstructures by connecting vessels.

Given Euler's equation for angular motion, assuming diagonalised inertia tensors with PMI $J_x$, $J_y$, $J_z$:

$$J_x\dot{\omega}_x = M_x - (J_z - J_y)\omega_y\omega_z$$
$$J_y\dot{\omega}_y = M_y - (J_x - J_z)\omega_z\omega_x$$
$$J_z\dot{\omega}_z = M_z - (J_y - J_x)\omega_x\omega_y$$

we represent each vessel by 6 samples $p_{1,2} = (\pm x,0,0)$, $p_{3,4} = (0,\pm y,0)$, $p_{5,6} = (0,0,\pm z)$ with

$$x = \tfrac{1}{2}\sqrt{|-J_x + J_y + J_z|}$$
$$y = \tfrac{1}{2}\sqrt{|J_x - J_y + J_z|}$$
$$z = \tfrac{1}{2}\sqrt{|J_x + J_y - J_z|}$$

The samples $p_i$ for each vessel are transformed into a common reference frame $p_i'$, given by the superstructure connectivity, and transformed PMI are constructed:

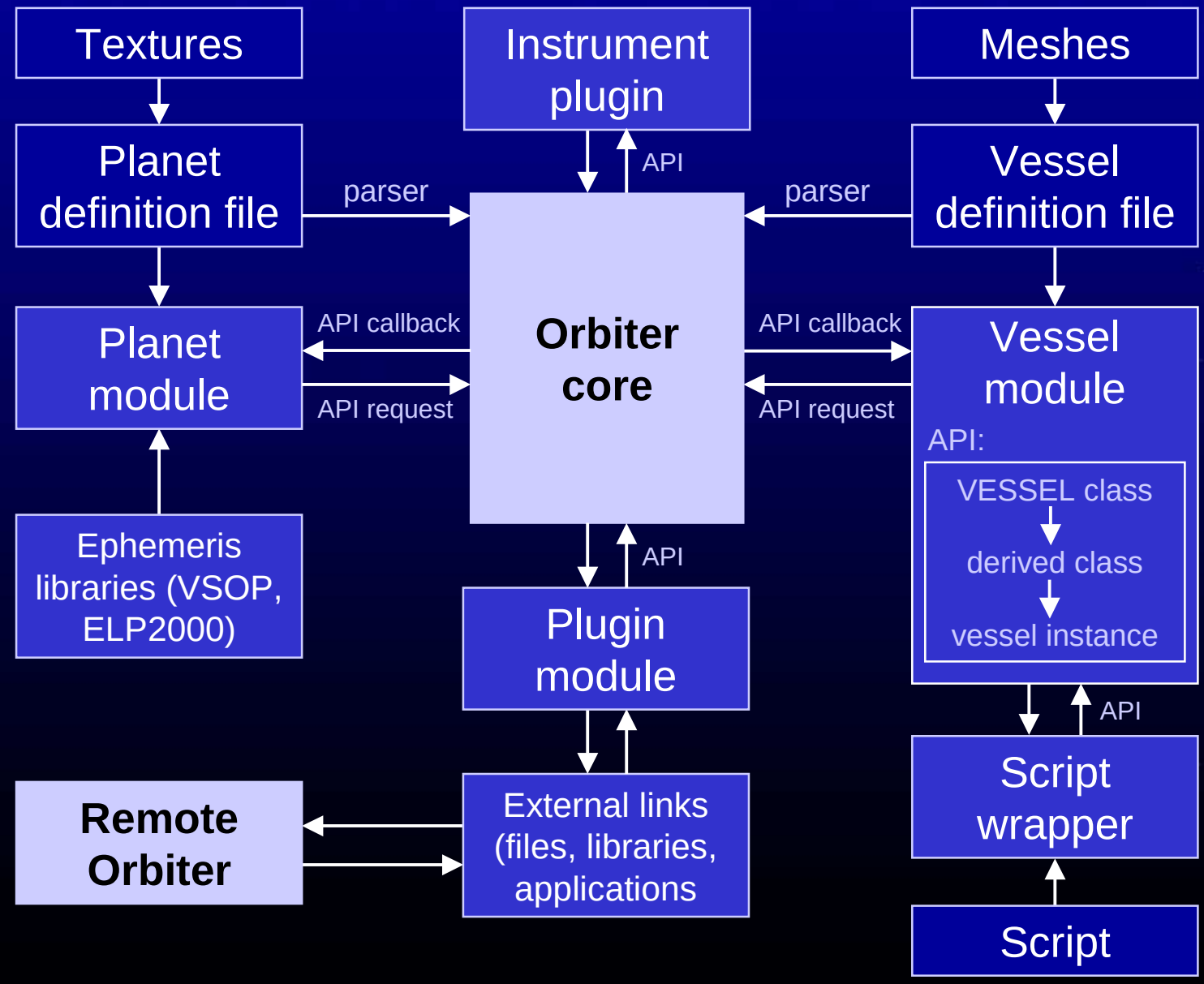
$$J'_x = m\sum_i y_i'^2 + z_i'^2$$
$$J'_y = m\sum_i x_i'^2 + z_i'^2$$
$$J'_z = m\sum_i x_i'^2 + y_i'^2$$

The PMI $J^{(S)}$ of the superstructure are then given by collecting all vessel contributions:

$$J^{(S)} = \sum_k J'^{(k)}$$

No off-diagonal elements are considered in $J^{(S)}$.

# Orbiter module design and API

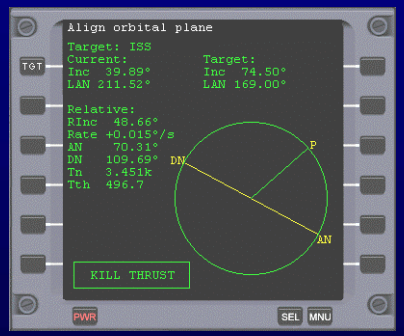


# Orbiter instrumentation

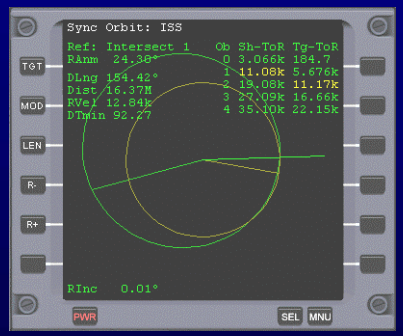
Multifunctional display (MFD) concept: seamless extension of instrumentation functionality via plugin MFD modes.

Generic instruments (selection):


Surface-relative and atmospheric parameters.



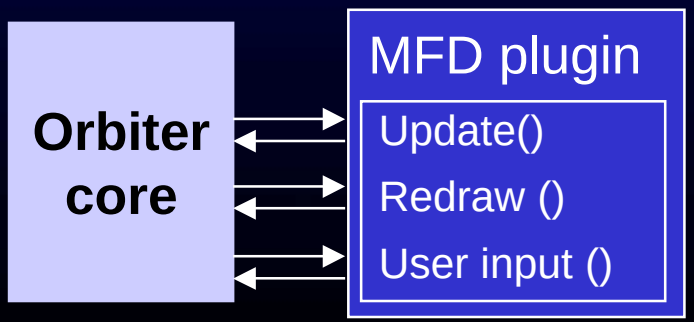

Align orbital plane with a target orbit at a node.

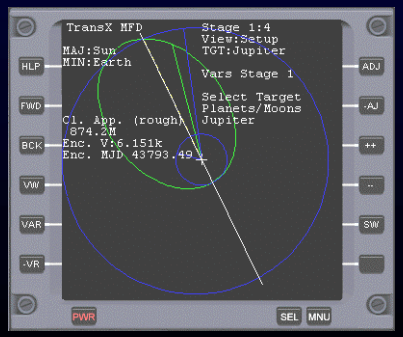



Rendezvous with target object.


Line up docking approach path.

Drop-in instruments from plugin modules:




TransX MFD mode: interplanetary transfer calculation with patched cone approach. (courtesy Duncan Sharpe)

# Orbiter API: The VESSEL interface

The VESSEL class is a generic interface between Orbiter and a vessel implementation.

callback functions

API get/set

```
class VESSEL
    clbkTimestep()
    clbkSaveState()
    ...
    GetAltitude()
    SetThrusterLevel()
    AddForce()
    ...
```

```
class myVessel: public VESSEL
    clbkTimestep()
    clbkSaveState()
    ...
    local_Functions ()
```

overloaded callback functions

Using Orbiter's built-in flight model:

Setup:
- Define_thruster ($\mathbf{r}$, $\mathbf{d}$, $f_0$, $isp$, ...)
- Define_airfoil ($\mathbf{r}$, $c_L(...)$, $c_D(...)$, ...)

Local calculation, bypassing Orbiter's flight model:

Time step:
- Get_Positions ()
- Get_Atmospheric_data ()
- ($\boldsymbol{F}$, $\boldsymbol{r}$) = local_Calculate_forces ()
- AddForce ($\boldsymbol{F}$, $\boldsymbol{r}$)

The vessel designer has a choice of using built-in flight models, or implementing a local model (using Orbiter as a visualisation framework only).

# Air-breathing engines: scramjet (1)

Scramjet design is an example for implementing a feature entirely externally without native support in the Orbiter core.

Ideal scramjet: temperature and pressure relationships

Diffuser: isentropic compression

$$T_d = T_\infty \left(1 + \frac{\gamma - 1}{2} M_\infty^2\right) \qquad p_d = p_\infty \left(\frac{T_d}{T_\infty}\right)^{\gamma/(\gamma-1)}$$

Combustion chamber: isobaric expansion

$$T_b = \max(T_{b0}, T_d) \qquad p_b = p_d$$

Exhaust nozzle: isentropic expansion

$$T_e = T_b \left(\frac{p_e}{p_b}\right)^{(\gamma-1)/\gamma} \qquad p_e = p_\infty$$

Jet engine propulsion thrust equation:

$$F = (\dot{m}_a + \dot{m}_f) v_e - \dot{m}_a v_\infty + (p_e - p_\infty) A_e$$

where $\dot{m}_a$ and $\dot{m}_f$ are the air and fuel mass rates, respectively, $v_e$ and $v_\infty$ are the exhaust and freestream velocities, and $A_e$ is the exhaust cross section.

# Air-breathing engines: scramjet (2)

Specific thrust is given by $\frac{F}{\dot{m}_a} = (1+D)v_e - v_\infty$

where $D = \dot{m}_f / \dot{m}_a$ is the *fuel-to-air ratio*.

The amount of fuel burned in the combustion chamber must be adjusted so that the burner temperature limit is not exceeded. This leads to the following expression for *D*:

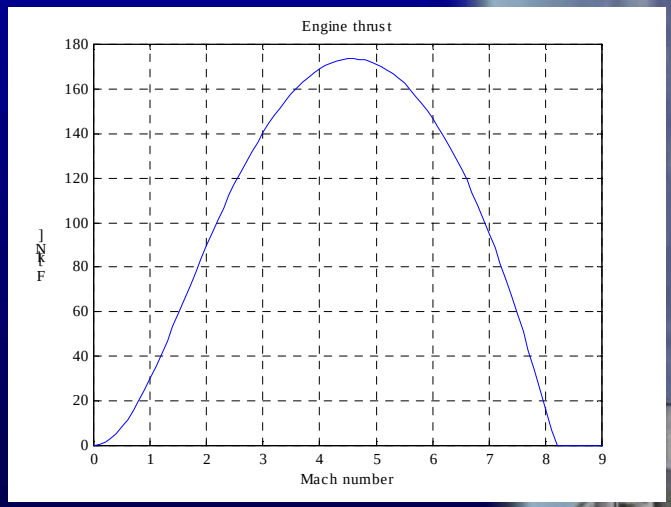
$$D = \frac{T_b - T_d}{Q/c_p - T_b}$$

where $Q$ is a fuel-specific heating value and $c_p$ is the specific heat at constant pressure, given by $c_p = \gamma R/(\gamma-1)$.

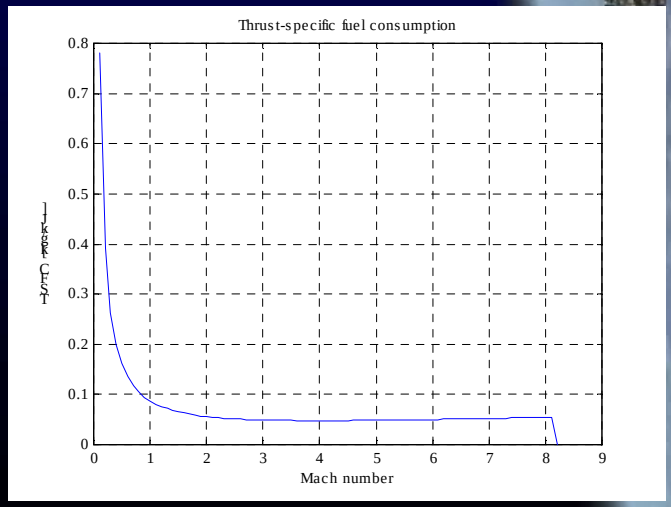
The exhaust velocity $v_e$ can be obtained from the energy balance

$$c_p T_b = c_p T_e + v_e^2/2$$

Thrust vs. Mach number:




TSFC vs. Mach number:



# Virtual 3-D Cockpit

- Support for 3-D virtual cockpit view
- Head rotation improves situational awareness
- “Eye-neck” offset generates movement parallax
- Camera reference point and rotation ranges defined by API calls
- Dynamic display updates
- Mouse-operated instruments
- Viewpoint-corrected HUD display

3-D artwork courtesy Roger Long

# New visual effects (1)

- Improved rendering of atmospheric haze at from high altitude
- Additional configuration parameters for colour distribution

- Rendering of objects through atmosphere layers is now additive.

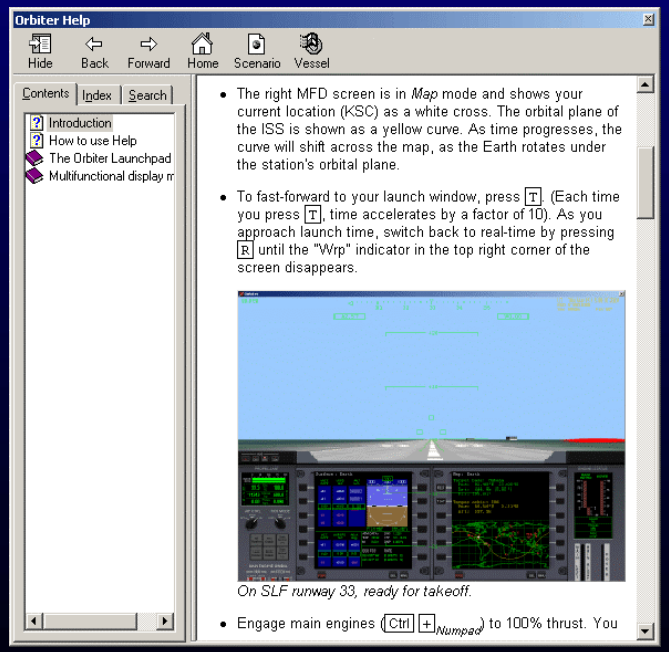
# New visual effects (2)

- Surface labels (launch sites, radio transmitters, user-defined)

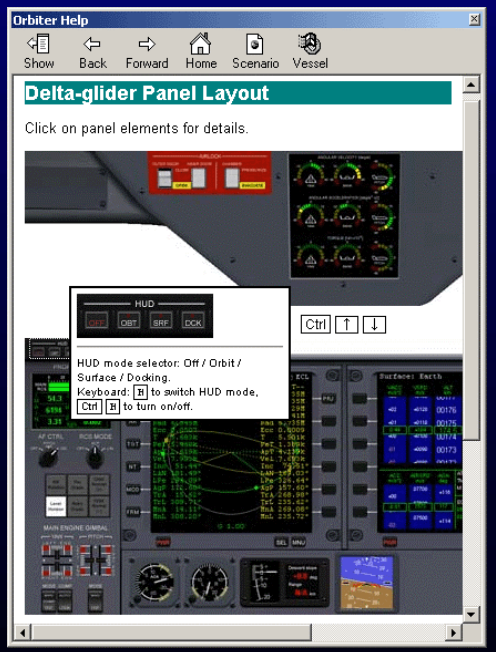
- Surface shadow support for structures and vessels

# Orbiter as a teaching tool

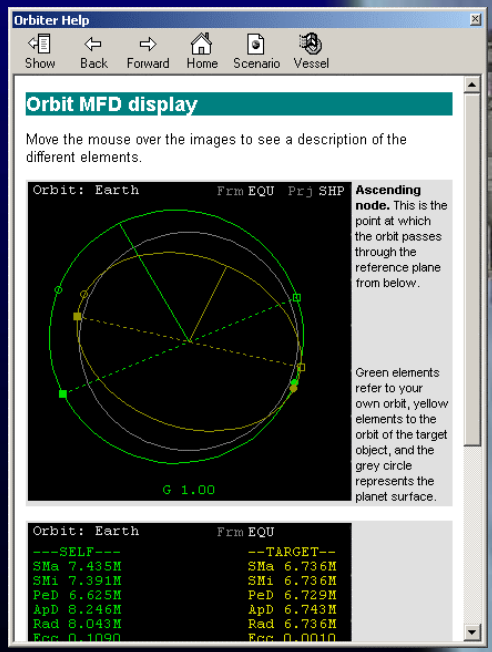
- New html-based help system (context-sensitive: scenario- and vessel-specific). Can be extended by 3rd party plugins.
- New "kiosk mode" for unsupervised use in public environments (limited simulation run time, automatic scenario selection).
- Flight data can be exported and analysed off-line.




Help system: scenario instructions




Help system: instrument layout and documentation




Help system: orbital mechanics primer

## Summary

- Orbiter is an accessible tool for atmospheric, orbital and interplanetary space flight simulation.
- Combining a (moderately) accurate physics engine with 3-D rendering, its main application is as an educational or recreational tool.
- The programming interface (API) is a versatile way to extend the core Orbiter functionality. Features not natively supported by the core can be added by external plugins.
- The API interface includes
  - state vector updates for celestial bodies
  - spacecraft implementations
  - instrumentation
- Development of the core module is ongoing, and a growing set of 3rd party contributions is available.

## Future developments

Some of the features planned for future releases include:

- Improvements of the flight model (stability of time integration, micro-drag, radiation pressure, atmospheric flight model).
- Damage and collision modelling.
- Multi-user support (simulation running on server continuously, clients connect temporarily).
- Elevation modelling of celestial bodies.

## Acknowledgements


| | |
|---|---|
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| Planet textures | James Hastings-Trew, Björn Jonsson, Dean Scott, Philip Stooke, Constantine Thomas, Robert Stettner, James Williams |
| The beta test team | |
| The addon developer base | |
| The sponsors | M6.net, avsim.com |


## Resources

Orbiter main site (includes download links and related sites):

www.medphys.ucl.ac.uk/~martins/orbit/orbit.html

www.orbitersim.com

Contact:

martins@medphys.ucl.ac.uk

Critique, suggestions and collaborations are very welcome.

< Orbiter Demonstration >