SMARTSAT
COOPERATIVE RESEARCH CENTRE

TECHNICAL REPORT 9

Assessing and Enhancing Multi-spacecraft Mission Simulation and Visualisation

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SWINBURNE UNIVERSITY OF TECHNOLOGY

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Executive Summary

Astrodynamics simulations provide a crucial input to space mission planning and operations. Interactive visualisation of mission configurations, particularly for multi-spacecraft constellations or formation-flying scenarios, play an important role in both understanding options and communicating outcomes to a variety of end users or audiences. Although the mathematical foundations of idealised orbital dynamics are well understood, in practice, spacecraft orbits are much more complex. This includes factors such as the interaction between a satellite with the local space environment (e.g., aerodynamic forces) or the impact of increasingly congested orbital zones and debris fields, which may require sudden orbit changes to avoid collisions. Mission simulation must now consider both individual satellites and multi-spacecraft configurations, which may include constellations sharing an orbit or satellites flying in a multi-aperture/multi-sensor formation.

The focus of this report is an examination and assessment of astrodynamics software tools for spacecraft mission planning, simulation, and visualisation. This includes an investigation of the capabilities of a suite of open source and commercial software options.

The research methodology employed a literature assessment of academic papers and technical reports that considered calculation of orbital dynamics, or demonstration of use cases linked to specific examples of commercial or open-source software. For each software option, consideration is given to factors such as:

- Technical requirements (platform, operating system, specifications)
- Availability of documentation and training materials
- Assessment of core functionality and level of extensibility
- Suitability for target applications in multi-spacecraft mission planning and operations
- Nature of visualisation modes supported for decision-making, project scoping, education, and communication.

Furthermore, engagement with SmartSat partners and end-user communities was carried out to establish specific needs for astrodynamics simulation and visualisation capabilities. This helped contribute to the selection of simulation software for evaluation as well as providing inputs to the development of metrics (e.g., accuracy of astrodynamics simulations, performance benchmarks, ease of use, financial factors) for an evaluation framework. The authors acknowledge the contributions of the organisations who generously contributed their time and insights.

Acronyms

3D	Three-dimensional
ASSET	Astrodynamics Software and Science Enabling Toolkit
ASTOS	Analysis, Simulation and Trajectory Optimisation Software
CAD	Computer-aided design
COTS	Commericial off-the-shelf
GMAT	General Mission Analysis Tool
GOTS	Government off-the-shelf
GUI	Graphical user interface
JAT	Java Astrodynamics Toolkit
MMSV	Multi-spacecraft Mission Simulation and Visualisation
MPS	Mission Planning Systems
Orekit	Orbits Exploration Kit
PIGI	Predictive Interactive Ground-station Interface
RSOC	Responsive Space Operations Centre
SCT	Spacecraft Control Toolbox
SDK	Software development kit
SoE	Sequence of Events
STK	Systems Tool Kit

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1 Background and Context

1.1 Introduction

Astrodynamics is the field of study concerned with the interaction between bodies in space, and the resulting complex dynamical motions that arise due to the influence of perturbing forces such as gravitational attraction. Astrodynamics combines celestial mechanics, attitude dynamics and aspects of positional astronomy to describe spacecraft motion, enabling the planning and analysis of missions [1]. More practically, astrodynamics tools are used for the design and analysis of spacecraft trajectories. This includes applications such as simulating orbits around planetary bodies – especially the Earth – and investigating the impact of propulsive manoeuvres that are used to transfer spacecraft around and between planets and moons in the solar system [2].

New spacecraft missions are expected to operate in complex dynamical environments, requiring modern designs with lower cost and higher efficiency. Ambitious trajectories for single and multi-element missions are dependent on accurate understanding of challenging gravitational environments and operational constraints [3].

To this end, software tools and techniques are necessary for the generation, optimisation, and analysis of orbital trajectories in support of the growing demands of current and future space missions. With the aim of improving mission planning and operations, the modern practice of astrodynamics utilises techniques from the simulation of dynamical systems, and other fields, to explore the chaotic dynamics of the planetary bodies. Computational astrodynamics focuses on the design and improvement of simulation methods and analysis tools that are used in planning, optimising and monitoring spacecraft trajectories [2]. Due to the intricacy and non-analytical nature of the systems involved, astrodynamics software tends to have both high algorithmic complexity and high-performance requirements to overcome the computational challenges encountered.

A brief overview of the fundamental concepts of astrodynamics, with a focus on some of the more important dynamic models, is now presented. These dynamical models often cannot be solved analytically and require the use of complex simulation techniques.

1.2 Overview of Astrodynamics Models

As described by Newton's Law of universal gravitation, gravity is the primary force that affects the motions of objects in free space. Here, there is a mutual gravitational attraction between any pair of objects with mass, producing a component of acceleration proportional to the individual masses and the inverse-square of their separation. The total force experienced by any object is a vector sum (i.e., considers both the direction and magnitude of the individual forces) over all such individual gravitational interactions. The resultant acceleration modifies the relative positions of all objects, leading to changes in the gravitational forces experienced.

When combined with other perturbing forces, the gravitationally induced motion of objects in space can become highly complex and difficult to describe analytically. In practice, not all the perturbing forces acting on a body in space are known perfectly, and both computational costs and approximation errors further complicate the process of simulation and analysis. As such, these systems are approximated via dynamical models which enable realistic (although approximate) trajectories to be designed and optimised in accordance with mission requirements. Such models can be deterministic, i.e., the future motion of any object depends only on the current state of the system – but are often non-linear, exhibiting chaotic effects in which even the tiniest perturbations result in significant deviations to future trajectories [2, 4, 5].

1.2.1 Keplerian Dynamics

Keplerian dynamics refers to the earliest, and simplest, approximation of orbital motion originally developed by Johannes Kepler to describe the observed motion of Mars. Kepler's establishment of the mathematical study of planetary motion was an important step on the road to the formulation of Isaac Newton's own Laws of motion and universal gravitation.

In the important case where there is a primary body in a system with a significantly higher mass than any other object (such as when considering the motion of planets around the Sun or a satellite orbiting the Earth), the much smaller acceleration experienced by the primary is negligible. Therefore, in the absence of any other forces, the orbit of a planet or satellite is an ellipse, with the primary located at one focus. The ellipse is one of the conic sections formed by the intersection of a flat plane with a cone. When applied to the motion of spacecraft, the conic sections include both bound orbits (ellipses and circles – a special case of an ellipse with an eccentricity of zero) and un-bound trajectories (parabolas and hyperbolas).

Keplerian dynamics are crucially important in astrodynamics, offering substantially simpler analytical approximations to real orbits. For many practical cases, excellent first approximations to spacecraft trajectories can be constructed or analysed under the Keplerian assumptions. Indeed, much of astrodynamics software is built around extensions of Keplerian dynamics, such as the patched conics approach of designing trajectories by joining ("patching") conic sections together, as well as non-Keplerian extensions for orbits affected by various perturbating forces [2].

1.2.2 High-Fidelity Orbital Dynamics

Modern astrodynamics research is concerned with the increasing complexity of new space mission architectures. Spacecraft are being designed under more demanding operational requirements for lower costs, higher efficiencies, better risk management, and more ambitious designs leading to enhanced scientific or commercial results [8]. Considering these greater demands, astrodynamics is turning increasingly to more complex methods and tools that are better suited to delivering relevant outcomes from a mission design process. A major component of these methods and tools is the use of higher-fidelity dynamical models that better capture the true non-linear behaviour of spacecraft motion in non-Keplerian regimes. These models extend beyond simple Keplerian dynamics and the two-body approximation by considering N-body dynamics for systems, where $N > 2$, resulting in spacecraft trajectories that can differ substantially from a simple ellipse.

N-body models are used to simulate a dynamical system of N bodies acting under mutual gravitational attraction, while ignoring the effects of special relativity. Newton's Laws of motion and universal gravitation combine to state that each point mass body experiences a total force that is the sum of all (N-1) interactions in the system. The problem with the N-body model is that it does not have a general closed-form solution that can be used to describe spacecraft trajectories [2, 4]. Rather, the positions and velocities are computed by means of simultaneous integration of a system of second-order differential equations. To simplify the system for integration, it is reduced to a first-order system by introducing a body's velocity as an additional set of state variables.

Modern trajectory design requires making trade-offs between simulation accuracy and the computational speed of design and analysis [1]. Restricted N-body dynamical models are employed to not only reduce the computational costs of simulating N-body dynamics, but to also uncover additional analytical insights that may further assist in the design of spacecraft trajectories [9]. Such models make it simpler to reason about complex orbital trajectories by introducing various restrictions and assumptions, building up into a hierarchy of simpler models that approximate the dynamics of more complex ones [10]. For example, since a spacecraft's mass is negligible in comparison to the body it orbits, its effect on such bodies can be ignored entirely, thereby restricting the model to simulate only the spacecraft's motion. Restricted N-body models mostly take the form of the Circular Restricted 3-Body Problem (CR3BP), the Elliptic Restricted 3-Body Problem (ER3BP), the Bicircular Restricted 4-Body Problem (BC4BP) or the Ephemeris Restricted N-Body Problem (Ephemeris NBP). In practice, these are used to design modern spacecraft trajectories in an increasing order of complexity.

1.3 Astrodynamics Simulation Software

Astrodynamical simulations provide a crucial input to space mission planning and operations. While the mathematical foundations of idealised orbital dynamics are well understood, in practice, spacecraft orbits are much more complex. This includes factors such as the interaction between a satellite with the local space environment (e.g., aerodynamic forces) or the impact of increasingly congested orbital zones and debris fields, which may require sudden orbit changes to avoid collisions. Mission simulation must now consider both individual satellites and multi-spacecraft configurations, which may include constellations sharing an orbit or satellites flying in a multi-aperture/multi-sensor formation.

Over many decades, the capabilities of computer-aided spacecraft system planning have increased, enabling new mission analysis and design methods. Advances in computer technology brought about the development of general mission design software solutions. The birth of three-dimensional (3D) computer graphics, driven in part by the needs of the computer gaming and entertainment industries, contributed to the creation of new visualisation tools: orbital mechanics problems can now be viewed in fully realistic, interactive 3D scenarios. Combining accurate trajectory propagation, simulation and visualisation capabilities within the same software suite provides mission designers a fully featured solution supporting mission analysis.

Astrodynamics simulation software enables activities to be performed at a system level where the system is often a spacecraft. This includes the simulation models and infrastructure needed to support investigation of specific design options, and capabilities to verify or validate operations of a space system. Originally, simulation and visualisation components may have been considered as support systems in an independent or uncoordinated approach [6]. When these components are used in a coherent way during the lifecycle of a mission, they can yield significant benefits by way of reducing risk and cost, acting as an enabling technology for a model driven development process [7].

Simulation and visualisation are used to support a wide range of operational activities during a spacecraft mission's lifetime. Some of the applications and benefits include:

- System performance predictions
- Verification and validation of software
- Validation of system requirements
- System test activities
- Operational development
- Identification of system faults
- Verification and validation of system performance requirements.

Through a growth in astrodynamics simulation and visualisation capabilities, there are opportunities to further support spacecraft mission and scenario planning, such as:

- Enhanced system prediction during the design process – this allows corrective measures (design modification) to be conducted
- Increasing reuse of models between different spacecraft
- Integration and exchange of different models
- Configuration of simulation activities in a feedback loop
- Development of high-accuracy digital twins.

1.4 Multi-spacecraft Mission Planning Systems

Spacecraft mission planning requires the careful coordination and modelling of all assets, and their constraints, which includes elements such as instrument and sub-system timing and synchronization, thermal properties, power consumption, data volume, geometry, visibility (to a ground station or network), and spacecraft pointing. Such tools, techniques, and methods are known collectively as Mission Planning Systems (MPS).

MPS also form a central part of ground segment operations, possibly having interfaces to many other ground segment systems, both inside and outside mission operations. This typically comprises input interfaces for incoming planning requests and updated external information like orbit and manoeuvre information, payload configuration updates, etc.

The wide variety of potential space missions requires planning tasks to be performed by differing systems under differing constraints, and as such, there is no one-size-fits-all approach to mission planning. Nonetheless, at the core of MPS there exists a generalised timeline representing a sequence of events (SoE) that is conflict free (i.e., can be executed on a spacecraft and on the ground without any errors, given a set of on-board and ground constraints), and ideally is as optimal as possible for a set of specific mission objectives. In addition, the timeline should maximize the usage of available resources and ensure that the goals of a mission are able to be met.

In the last decade, missions involving multiple spacecraft working together autonomously have become of great interest, as they offer several scientific and engineering advantages. This trend is responsible for an increasing demand on mission planning systems to coordinate different spacecraft and to allocate tasks amongst them. New mission approaches are being designed and developed to handle this new level of complexity, combining autonomous solutions for both ground and space segments.

1.5 Purpose and Aims of this Study

Not all astrodynamics simulation and visualisation solutions have been designed with multi-spacecraft scenarios in mind. Moreover, new mission opportunities are increasing both the size and the expectations of end user communities, particularly within Australia, as local space industries are progressing through a period of unprecedent growth.

To increase the capability and scale of Australian involvement in space mission planning, this work investigates the state-of-the-art in astrodynamics simulation and visualisation software and frameworks, including both commercial and open-source alternatives. The overall aim is to inform future SmartSat activities, where improvements in software usability, performance, or accessibility would advance Australia’s capabilities in mission simulation, operations, and space situational awareness activities.

Specifically, this study assesses the suitability, usability, and flexibility of existing state-of-the-art commercial and open-source astrodynamics simulation software for use in planning and promoting multi-spacecraft missions. The assessment considers relevant technical aspects along with the ease with which different SmartSat end-user communities can access or use the software, recognising that there are different requirements, and expectations, from novice, intermediate, or expert users. The visualisation capabilities of the software packages are also examined to determine how they might be used to both assist in mission planning and scenario exploration activities.

The remainder of this report is structured as follows:

- Section 2 presents a review of software tools for space mission simulation and visualisation. This is derived from a literature assessment of relevant academic publications, white papers and technical reports detailing calculations of orbital dynamics, demonstration of use cases linked to specific examples of commercial or open-source software, and evaluation of the accuracy of astrodynamics simulations. This process helped to identify the most relevant broad suite of astrodynamics simulation and visualisation software for evaluation.
- Section 3 summarises the results of a SmartSat partner and end-user consultation process, providing perspectives, requirements, and synthesising key lessons learnt. This section also addresses down-selection to the most relevant software options based on issues such as cost, availability, functionality, and support for multi-mission scenarios.
- Concluding remarks are presented in Section 4.

2 Review of Software Tools for Mission Simulation and Visualisation

Astrodynamics simulation and visualisation software toolkits have become popular due to their increasingly robust decision-making, timesaving, and cost-effectiveness characteristics. Although space missions pose numerous evaluation and test challenges, these are mostly overcome by way of modelling, simulation, and visualisation of spacecraft mission parameters. Nowadays, developing a complex project without the assistance of a software toolkit is practically impossible.

In space technology, and especially space missions design, the importance of simulation, visualisation, modelling, and analysis cannot be underestimated. Collectively, they have become vital tools in the design and verification of space missions, which can be applied from project conception to the operation phase of a mission’s lifecycle, providing stakeholders safe and cheap options [6]. These tools are used for design and development throughout the spacecraft system lifecycle and thus may show up in different applications for different purposes e.g., sizing of system elements, subsystem simulations, simulation of spacecraft functional behaviour, or even entire spacecraft environment and ground station visualisation [12, 13].

Space mission simulation and visualisation software toolkits are important as they enable the design space to be explored more broadly, thus helping to identify and facilitate suitable candidate system solutions for a mission [11]. Moreover, space mission software can reduce the time required in integrated concurrent design environments, which are necessary for maintaining mission accuracy.

Innovations in software toolkits for space missions are transforming the way space activities are investigated. Spacecraft are becoming more software-intensive to support due to: (i) smarter remote control and autonomous operations; (ii) improved productivity for science data gathering and analysis; (iii) better troubleshooting; and (iv) an accelerated understanding of our local planetary environment and the universe [7].

Advances in software engineering play a critical role in space exploration by providing tools, techniques, and a systematic approach to develop and serve the many kinds of software needed for robust simulation, modelling, analysis, and deep-space discovery. In addition, software for mission control is progressing rapidly, with scope for further enhancement through the utilisation of new computational and algorithmic capabilities. For example, data modelling and visualisation capabilities for spacecraft analysis spanning multiple data sets, distributed platforms and operations, operator use cases, accessible data and spacecraft reconfiguration capabilities are driving the needs for new software solutions.

Of relevance to the present study, analysis and simulation of spacecraft trajectories is required throughout the entire lifetime of a space mission. Designing a suitable trajectory requires access to reliable physical or dynamical models. Additionally, robust propagation algorithms are needed that can allow optimisation and examination of potential trajectories for their viability considering several factors such as fuel used, flight path, collision avoidance manoeuvres, etc. [14].

End users for space mission planning and operations span a range of technical skill levels from novice to expert. As the majority of astrodynamics simulation and visualisation solutions target the expert end of the scale, this can present a barrier to entry. Additionally, as new software solutions and algorithms for calculating orbital properties are developed, it can be challenging to determine which is the most suitable solution to use – where suitability may include both quantitative (how accurate is the orbital calculation and over what time period?) and qualitative (how easy is the software to use to accomplish a mission scoping activity?) factors. Well-established options, such as the Systems Tool Kit (see Section 2.2.1) developed by AGI, provide a great deal of functionality but with individual license costs that may be prohibitive (USD$4K- $21K, depending on the level of access required), may be performance-limited based on available hardware, or have some features (e.g., cloud delivery) restricted to a limited number of nations. Newer options are favouring an open-source approach (e.g., Basilisk – Section 2.2.4), but may have a smaller existing community to assist with the development, testing, or to provide on-going support.

2.1 Technical Requirements

A wide variety of tools exist for performing mission simulation and visualization, however, software solutions mostly come in two forms: (i) mission specific; and (ii) general software. Mission specific software is oftentimes highly specific and difficult to adapt to other missions, while general software presents a solution that supports a variety of mission types. Here, there exist expensive, yet well established, commercial software options and free open-source alternatives. Other integrated solutions can serve specific purposes, such as modelling of spacecraft trajectories.

Table 1 presents a summary of the technical specifications for a suite of astrodynamics and open-source software that are currently being utilised within the astrodynamics community for multi-spacecraft mission simulation and visualisation (MMSV). Recognising that this list is not exhaustive, the options selected aim to capture many of the most used packages. The summary considers the source status (which is usually linked to the licensing conditions, such that open-source software is often free for use and modification, while proprietary software is usually closed source and requires a license fee for use), platform, operating system and, where information was readily available, the main development language, libraries, or standard tools utilised. Based on the overall list, we performed a down-selection of options for further investigation (Section 2.2 and 2.3).

TABLE 1. MULTI-SPACECRAFT MISSION SIMULATION AND VISUALISATION (MMSV) SOFTWARE OPTIONS INVESTIGATED, AND THEIR TECHNICAL REQUIREMENTS. SOURCE TYPES ARE OPEN (OPEN SOURCE) OR PROP (PROPRIETARY, WHICH USUALLY IMPLIES CLOSED SOURCE). THE SECTION ENTRY IDENTIFIES THE RELEVANT SECTION OF THIS REPORT WHERE SPECIFIC PACKAGES ARE DESCRIBED.

Software	Source	Platform	OS	Implementation	Section
ASSET: Astrodynamics Software and Science Enabling Toolkit	Open	Desktop	Linux Windows	C++ / Python	
ASTOS: Analysis, Simulation and Trajectory Optimisation Software	Prop	Desktop	Linux MacOS Windows	Unconfirmed	2.2.9
Basilisk	Open	Desktop	Linux MacOS Windows	C / C++ / Python	2.2.4
Cesium	Open	Desktop	Linux Windows	Java	2.3.1
Celestia	Open	Desktop Mobile	Android Linux MacOS Windows	Unconfirmed	2.3.2
Copernicus Trajectory Design and Optimisation System	Prop	Desktop	Linux MacOS Windows	Python	
DARTS: JPL - Dynamics Algorithms for Real-Time Simulation/Dshell	Prop	Desktop	Linux Windows	C++ / Python	
FreeFlyer	Prop	Desktop	Linux Windows	.NET / C++ / C# / Python / Java	2.2.2
GMAT: General Mission Analysis Tool	Open	Desktop	Linux MacOS Windows	C++	2.2.3
GMV	Prop	Desktop	Windows	Fortran	
JAT: Java Astrodynamics Toolkit	Open	Desktop	Linux	Java	2.2.7
MATLAB SATCOM Toolbox	Prop	Desktop	Linux MacOS Windows	MATLAB	
Orekit: ORbits Exploration Kit	Open	Desktop Web Mobile	Linux MAC OS Windows	Java	2.2.5

Table 2. Continued.

Software	Source	Platform	OS	Implementation	Section
Open-SESSAME: Open-Source, Extensible Spacecraft Simulation and Modelling Environment	Open	Desktop	Linux MAC OS Windows	C++	
ORSA: Orbit Reconstruction, Simulation and Analysis	Open	Desktop	Linux MAC OS Windows	C++	2.2.6
PIGI: Predictive Interactive Ground-Station Interface	Prop	Desktop Web	Linux MAC OS Windows	Python	2.2.8
Poliastro	Open	Desktop	Linux MAC OS Windows	Python	
SCT: Spacecraft Control Toolbox	Prop	Desktop	Linux MAC OS Windows	MATLAB	2.2.10
Space Planet Instrument C-matric Event (SPICE) toolkit	Open	Desktop	Windows	C / Python / MATLAB / IDL / JAVA / FORTRAN	
STK: Systems Tool Kit	Prop	Desktop	Linux Windows	.NET / Cesium Analytic SDK / JAVA	2.2.1

2.2 Software Toolkits for Space Simulation and Visualisation

A brief overview of the functionality and purpose of several leading commercial and open-source software toolkits for space mission simulation and visualisation are now reviewed, with attention paid to technical requirements.

2.2.1 Systems Tool Kit (STK)

Systems Tool Kit (STK) [15], formerly known as Satellite Tool Kit, is an indispensable digital mission engineering application for complex mission systems on air, sea, land, and space.

STK operates as a visualisation and analysis tool, which can estimate satellite system performance and deliver results through customisable reports, mission simulations, and graphs. Specific functionalities are provided through modules, which includes orbital mechanics models [16]. See reference [15] for a description of the detailed architecture of the STK software.

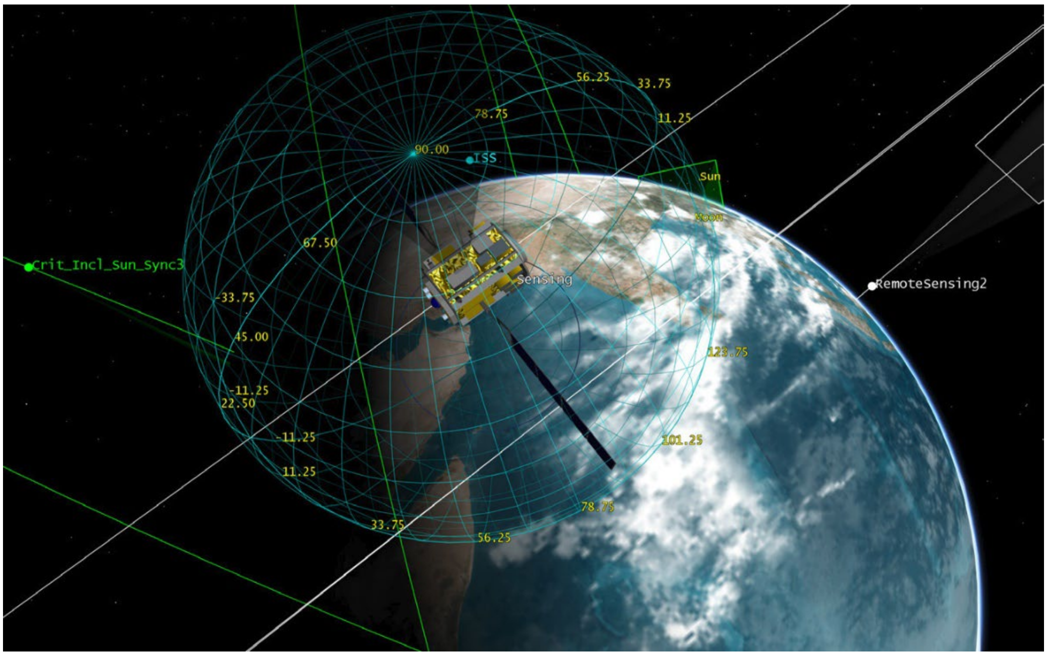


Figure 1. An example of the STK visualisation interface [15].

STK is used in aerospace, defence, telecommunication, and other industries. STK features an accurate, physics-based modelling environment to analyse platforms and payloads in a realistic mission context by exploring the performance of complex systems with a focus on their operational environments as shown in Figure 1. Furthermore, STK can simulate an entire system-of-systems in action, at any location and at any time, allowing users (e.g., mission planners, spacecraft operators) to gain a clear understanding of system behaviour and mission performance.

Amongst some of STK's key capabilities are:

- Communication modelling
- Radar modelling
- Electro-optical and infrared (EOIR) modelling
- Astrogator (interactive orbit manoeuvre and spacecraft trajectory design)
- Conjunction analysis
- Test and evaluation
- Coverage (determination of response and revisit times based on space visibility)
- Analysis workbench
- Integration and customisation
- Parallel computing
- Reporting and visualisation

Although STK does offer a free basic version, the modules required for most applications are not free. As consultation with end-users demonstrated (see Section 3), STK can be perceived as a costly solution. STK has three tiered categories offering slightly different simulation and visualisation functionalities: (i) STK Pro; (ii) STK Premium, which consists of space and air models; and (iii) STK Enterprise.

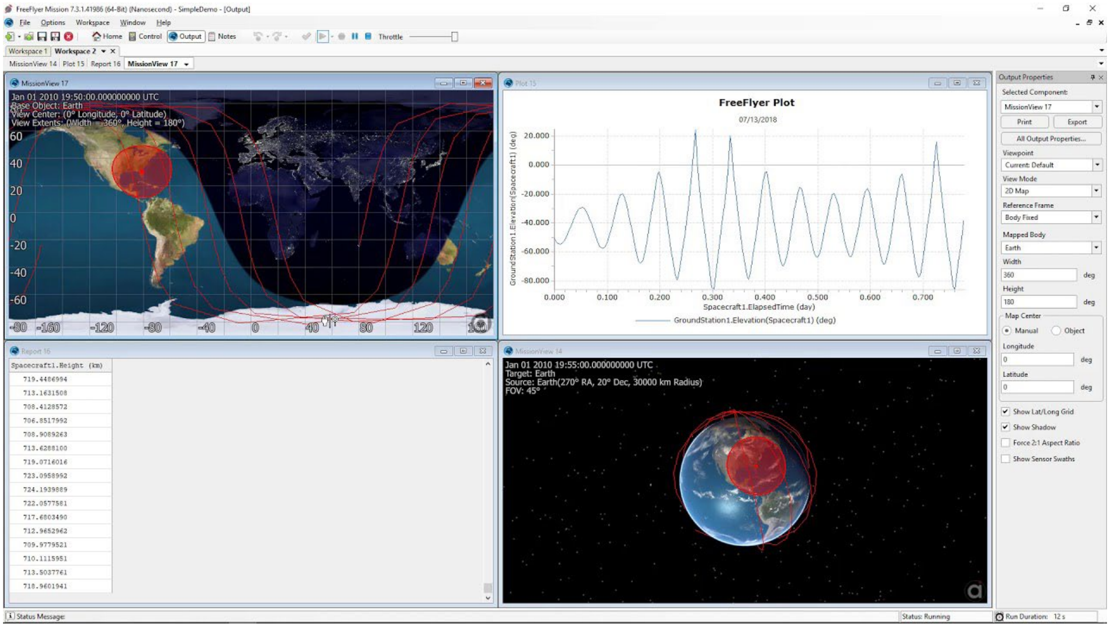
STK Pro provides a foundation for analysing and visualising complex systems in a mission. This version also supports the creation of multi-domain scenarios that extend simulation beyond systems to an interactive model of the operational environment. The functionalities of STK Pro can be accessed via documented application programming interfaces (APIs) to automate workflows, integrate workflows with other applications, or create customised tools [15].

STK Premium builds on the capabilities of STK Pro by conducting higher fidelity modelling of platforms and subsystems. This includes advanced analytical tools to help understand system performance and design capabilities. The space model adds advanced modelling of space-based platform and payload systems to STK Pro, including advanced orbit design and manoeuvre planning for satellite and spacecraft missions. The air model adds advanced modelling of aircraft platforms and payload systems.

STK Enterprise combines all of STK's digital mission engineering software toolkits to meet the demands of institutions with multi-domain projects, as well as providing data management solutions and analysis tools for test and evaluation.

2.2.2 FreeFlyer Astrodynamics Software

FreeFlyer Astrodynamics Software [17], from A.I. Solutions, is a commercial off-the-shelf (COTS) solution that can solve both simple and complex astrodynamics problems. FreeFlyer supports all phases of a mission lifecycle, from mission analysis and initial design studies through to automated on-orbit operations. As opposed to STK, FreeFlyer does not utilise a modular base – it is available as a single, self-contained package at an initial license cost, with an on-going annual maintenance cost [16].



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View Center: (0° Longitude, 0° Latitude)
View Extents: (Width = 360°, Height = 180°)

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    713.1631508
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    706.8517992
    708.9089263
    713.6288100
    719.0716016
    723.0958992
    724.1939889
    722.0577581
    717.6803490
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    709.9779521
    710.1115951
    713.5037761
    718.9601941
```

Jan 01 2010 19:55:00.000000000 UTC
Target: Earth
Source: Earth(270° RA, 20° Dec, 30000 km Radius)
FOV: 45°

Selected Component: MissionView 17
Viewpoint: Current: Default
View Mode: 2D Map
Reference Frame: Body Fixed
Mapped Body: Earth
Width: 360 deg
Height: 180 deg
Map Center: ● Manual ○ Object
Longitude: 0 deg
Latitude: 0 deg
☑ Show Lat/Long Grid
☑ Show Shadow
☐ Force 2:1 Aspect Ratio
☐ Show Sensor Swaths

Status: Running
Run Duration: 12 s

Figure 2. Examples of the FreeFlyer graphical user interface and visualisation interface [17].

FreeFlyer's capabilities include:

- Mission engineering and technical services. Delivering full lifecycle space mission engineering and technology services including satellite operations, flight dynamics analysis, sustaining engineering, ground systems development, program management and facilities management.

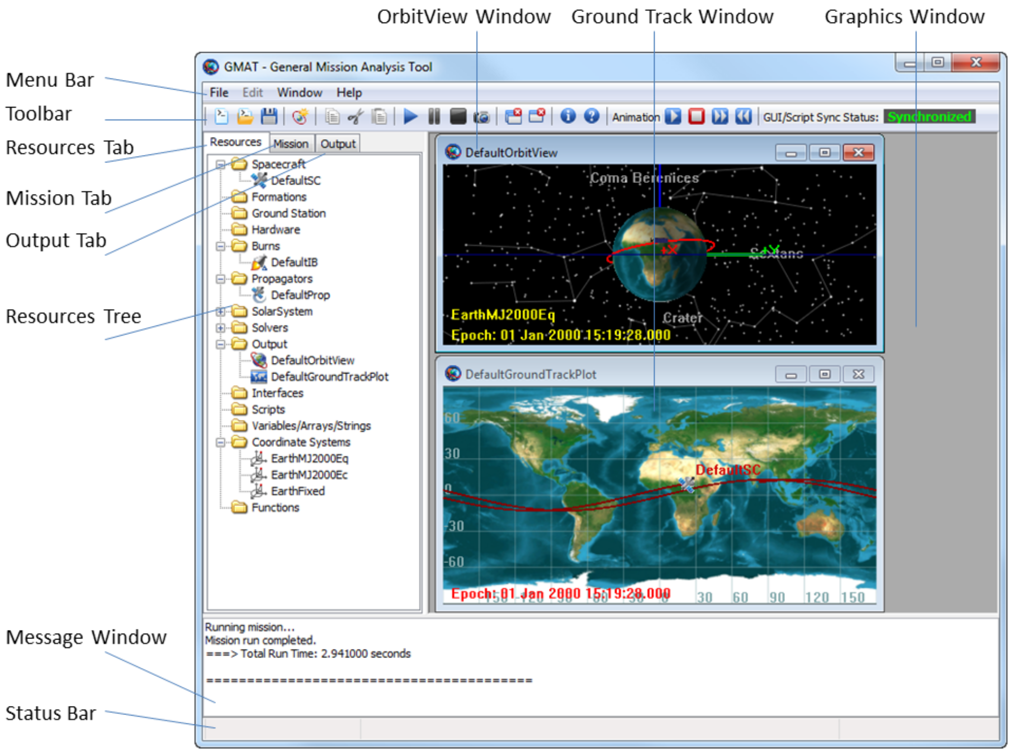
- Modelling and simulation. Customised support for modelling and simulation services with areas of expertise such as spacecraft flight dynamics analysis and algorithm development for formation and constellation design, coverage, and communication analysis, launch analysis and sensor monitoring.
- Software engineering. Developing flight dynamics from ground systems to facility modernisations and automation. FreeFlyer uses both COTS and mission-unique software platforms to design space mission applications for routine and bespoke astrodynamics functionality.
- Mission operations. Provides real time, routine and non-real time mission operations for expendable launch vehicles, manned spaceflight and spacecraft payload mission, multi-mission space operations. FreeFlyer's mission operations services include orbit and attitude determination, manoeuvre planning, data evaluation and tracking.
- Deep space trajectory explorer. A COTS interactive software package that combines cutting-edge multibody trajectory design techniques with innovative visualisations to reduce time spent on trajectory design. It allows intuitive selection of orbits that satisfy mission constraints. Designed for any planet-moon system.

FreeFlyer adopts a tiered system approach with increasing functionality where each tier adds to the previous. The design tier provides an analysis tool for mission concept development and preliminary design. The engineering tier offers more complex modelling and comprehensive mission analysis and design functionality. The mission tier provides complete spacecraft mission design and operations functionality as shown in Figure 2. The design framework for FreeFlyer is illustrated in reference [17].

2.2.3 General Mission Analysis Tool (GMAT)

The General Mission Analysis Tool (GMAT) is a platform independent multi-mission, open-source software system for space mission design, optimization, and navigation. The system supports missions in flight regimes ranging from low Earth orbit to lunar, libration point, and deep space missions. GMAT was developed collaboratively by NASA, private industry, public, and private contributors, and is used for real-world mission support, engineering studies, and as a tool for education and public engagement.

GMAT provides a system containing high fidelity space system models, optimization and targeting, built in scripting and programming infrastructure, and customizable plots, reports, and data products, to enable flexible analysis and solutions for custom and unique applications [18]. GMAT is operated via a fully featured, interactive graphical user interface (GUI) or from a custom scripting language. Users create and configure resources, such as spacecraft, propagators, and optimizers, which are later used in the mission sequence to model the spacecraft motion. This is often accomplished by using the GUI, as illustrated in Figure 3.



```
Running mission...
Mission run completed.
===> Total Run Time: 2.941000 seconds

=============================================
```

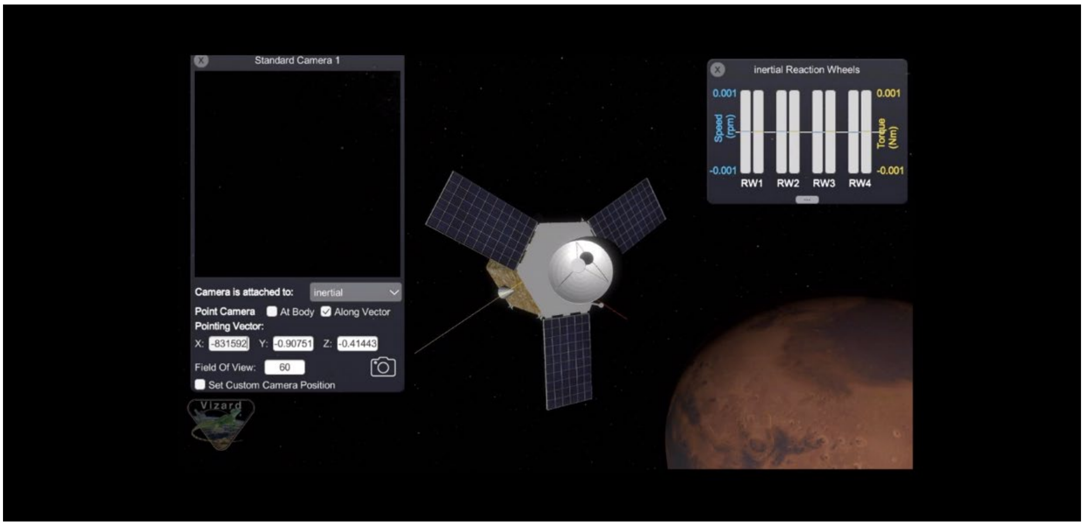
Figure 3. Example of the GMAT graphical user interface [19].

Some of the main features available in GMAT include:

- Dynamics and Environment Modelling
    - High fidelity dynamics models including harmonic gravity, drag, tides, and relativistic corrections
    - High fidelity spacecraft modelling
    - Formations and constellations
    - Impulsive and finite manoeuvre modelling and optimization
- Plotting, Reporting and Product Generation
    - Interactive 3-D graphics
    - Customizable data plots and reports
    - Post computation animation
- Optimization and Targeting
    - Boundary value targets
    - Nonlinear, constrained optimization
    - Custom, scriptable cost functions
- Programming Infrastructure
    - User defined variables, arrays, and strings
    - User defined equations using MATLAB syntax.
    - Built in parameters and calculations in multiple coordinate systems.

2.2.4 Basilisk

Basilisk is a fast, open-source spacecraft-centric mission simulation framework capable of faster-than real time spacecraft simulations, including repeatable Monte-Carlo simulation options [20]. The package is designed as a set of Python modules, which allows for ease of scripting and reconfiguration while providing the maximum execution speeds [21]. Basilisk was jointly developed by the University of Colorado's Autonomous Vehicle Systems (AVS) Lab and the Laboratory for Atmospheric and Space Physics (LASP).



Camera is attached to: inertial
Point Camera ☐ At Body ☑ Along Vector
Pointing Vector:
X: -831592 Y: -0.90751 Z: -0.41443
Field Of View: 60
☐ Set Custom Camera Position

Figure 4. An example of the Basilisk graphical user interface [20].

The Basilisk framework models the orbit and attitude of complex spacecraft systems, as well as sophisticated mission-specific vehicle simulations that include hardware-in-the-loop scenarios. Basilisk uses a companion visualisation program known as Vizard [22] – a standalone program based on the Unity rendering engine – which displays the software simulation states in an interactive manner [20]. An example of the Basilisk user interface is shown in Figure 4.

Basilisk is actively used for modelling complex spacecraft dynamic behaviours including:

- Developing new guidance, estimation, and control solutions
- Supporting mission concept development
- Flight software development
- Hardware in the loop testing by simulating real time spacecraft states
- Analysis of flight data
- Supporting spacecraft artificial intelligence (AI) based autonomy development.

A comprehensive overview of Basilisk software as well as its internal architecture and functionalities can be found in reference [20, 21].

2.2.5 Orbits Exploration Kit (Orekit)

Developed in 2002 by the CS Systèmes d'Information, Toulouse, France. Orekit, was intended as an in-house asset to serve as a basis for custom systems designed for its customers [23]. It represents a low-level space dynamics library implemented in Java and Hipparchus [24] (version 1.0 or above) libraries at runtime. The library transformed from a small set of core components to a fully-fledged collection of algorithms that provides basic elements such as reference frames, times, bodies, orbits, attitude, etc.

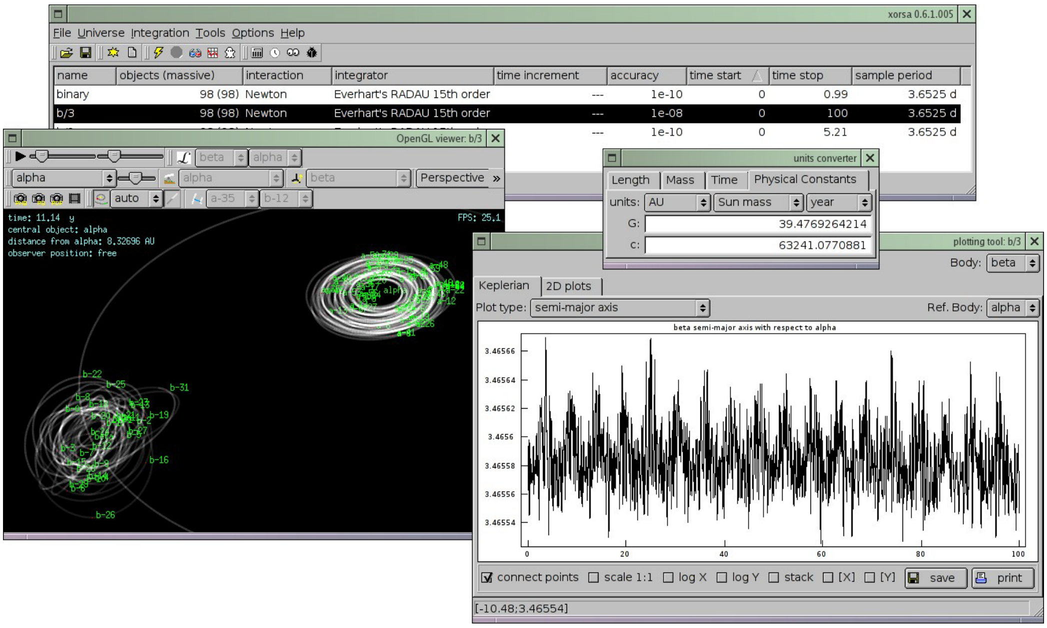
Presently, Orekit is published as an open-source code provided under the Apache license (version 2.0) with all related tests and documentation [25]. Use cases for Orekit range from simple geometrical or orbital tools to complex orbits propagators with several perturbing forces, manoeuvres, and discrete events. The characteristics features of the library include time, geometry (frames, Inertial Earth Reference Frame conventions, etc), spacecraft states, manoeuvres, propagation (analytical, numerical, tabulated ephemerides, predefined discrete events, semi-analytical, etc), orbit determination, attitude, global navigation satellite systems (GNSS), orbit handling files, collisions, various Earth models and customisable data solutions. Orekit is widely recognised and is being used by the European Space Agency (ESA) and has been used by the Centre National d'Etudes Spatiales (CNES, the French Space Agency) as the basis for its next generation space flight dynamics systems since 2011.

2.2.6 Orbit Reconstruction, Simulation and Analysis (ORSA)

ORSA is a framework for scientific grade celestial mechanics computations with the goal of implementing state of the art orbit integration algorithms with concerns on accuracy, performance, and the development of a number of interactive and analysis tools [26]. The main objective of ORSA is to create a common infrastructure among other mechanics programs and to provide support for high throughput computing systems. ORSA is currently free software but with a GPL license.

Some of the main features of ORSA are presented below, with an example of the graphical user interface shown in Figure 5:

- Accurate numerical algorithms
- Qt-based graphical user interface
- Advanced 2D plotting tool and 3D OpenGL viewer
- Integrated download tool to update databases
- Standalone numerical library liborsa
- Multipole Expansion (useful for low-Earth artificial satellites).



name	objects (massive)	interaction	integrator	time increment	accuracy	time start	time stop	sample period
binary	98 (98)	Newton	Everhart's RADAU 15th order	---	1e-10	0	0.99	3.6525 d
b/3	98 (98)	Newton	Everhart's RADAU 15th order	---	1e-08	0	100	3.6525 d
				---	1e-10	0	5.21	3.6525 d

time: 11.14 y
central object: alpha
distance from alpha: 8.32696 AU
observer position: free

units: AU Sun mass year
G: 39.4769264214
c: 63241.0770881

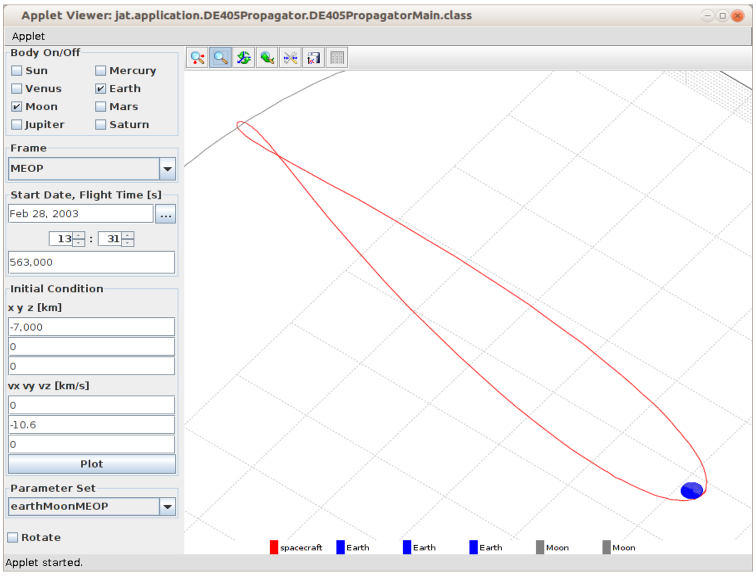
Body: beta
Plot type: semi-major axis
Ref. Body: alpha

[-10.48;3.46554]

Figure 5. An example of the ORSA graphical user interface [26].

2.2.7 Java Astrodynamics Toolkit (JAT)

The Java Astrodynamics Toolkit (JAT) is an open-source software library with cross platform capabilities. It supports quick development of spacecraft simulations and visualisation capabilities as illustrated in Figure 6. The library uses software components for its mission design, attitude determination, spacecraft navigation and analysis, guidance and control systems, and trajectory optimisation approaches [27]. Some of its capabilities include orbit propagation, 2D/3D attitude and orbit visualisation, manoeuvre planning, time systems and coordinate transformation, ground tracking or Global Positioning System measurements for orbit determination and attitude simulation. An in-depth overview of JAT's internal architecture and capabilities can be found in references [28, 29].



Applet Viewer: jat.application.DE405Propagator.DE405PropagatorMain.class

Body On/Off

☐ Sun ☐ Mercury

☐ Venus ☑ Earth

☑ Moon ☐ Mars

☐ Jupiter ☐ Saturn

Frame: MEOP

Start Date, Flight Time [s]: Feb 28, 2003; 13 : 31; 563,000

Initial Condition

x y z [km]: -7,000; 0; 0

vx vy vz [km/s]: 0; -10.6; 0

Parameter Set: earthMoonMEOP

☐ Rotate

Applet started.

Figure 6. An example of the JAT visualisation interface [29].

2.2.8 Predictive Interactive Ground-Station Interface (PIGI)

The Predictive Interactive Ground-Station Interface (PIGI) is an interactive software solution used for mission planning, design, and spacecraft operations. PIGI was developed by Saber Astronautics [30].

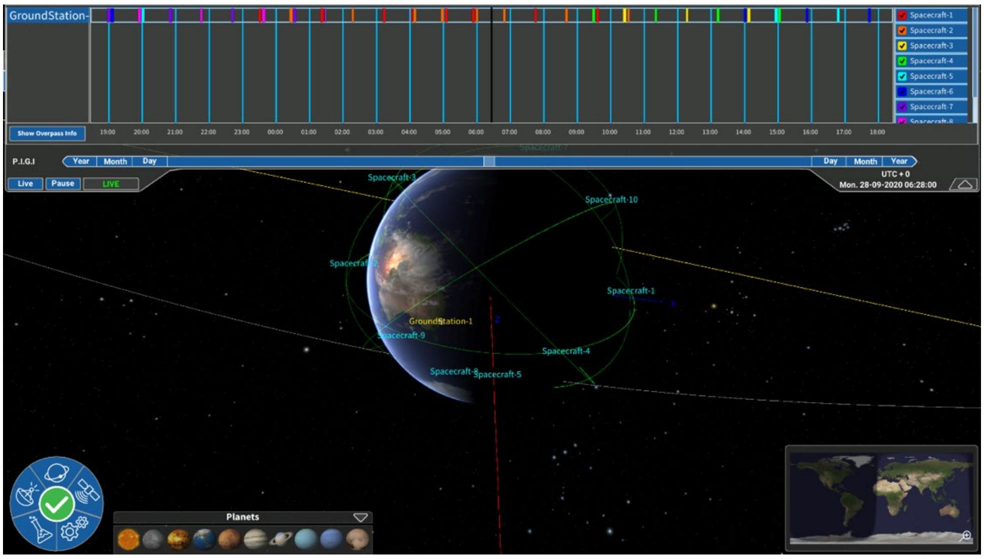


Figure 7. PIGI graphical user interface and visualisation interface [31].

PIGI capabilities include:

- Monitoring and control of spacecraft systems and payload
- Manoeuvre preparation and orbital design
- Management of onboard software
- Spacecraft performance and analysis and reporting
- Control of mission operations
- Delivery of mission data products.

A casual license exists for PIGI, which provides users with an indication of the basic capabilities and is suitable for training and mission planning. The more advanced versions of PIGI are used for satellite control and debris tracking, through the operation of the Responsive Space Operations Centre (RSOC) in Adelaide, Australia and Boulder, Colorado. PIGI uses open-source tools and other support systems, such as a satellite constellation maker and computer-aided design (CAD) importer tools for its visualisation capabilities. Figure 6 shows both the GUI and visualisation interface of PIGI.

2.2.9 Analysis, Simulation and Trajectory Optimisation Software (ASTOS)

ASTOS is a multi-purpose tool for space applications. Originally designed for trajectory optimisation, it provides modules for a variety of analysis, simulation, and design capabilities for the life cycle of a mission [32]. It contains built-in plotting, animation, and visualisation tools (Figure 8) that support a range of scenarios and applications.

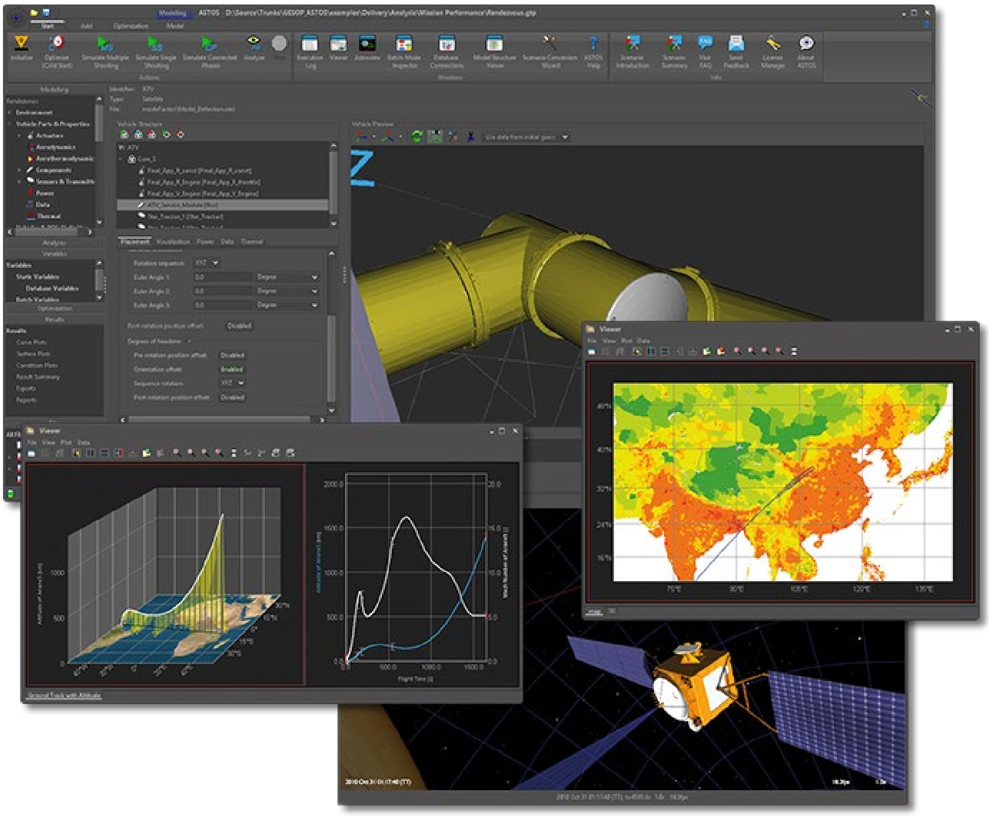


Figure 8. An example of the ASTOS graphical user interface and visualisation interface [33].

ASTOS has a variety of interfaces that can be easily integrated into any interdisciplinary working environment e.g., SQL databases, Microsoft Excel-format import and export, as well as specialised data formats as per recommendations of the Consultative Committee for Space Data Systems.

Some of the key features of ASTOS include:

- Built-in trajectory and multi-disciplinary design optimisation
- Rigid and flexible multi-body dynamics
- Wide range mission analysis features, performance, and system concept analysis features
- Launch and re-entry safety analysis, built-in plotting, animation, and visualisation tools
- Simulink and dSPACE interfaces for closed loop simulations
- Built-in batch-processing engine, and configuration tool.

ASTOS main supporting functionalities are in optimisation, mission & spacecraft design, mission performance analysis, system concept analysis and guidance, navigation and control/attitude orbit control systems analysis. Further information can be found in reference [33].

2.2.10 Spacecraft Control Toolbox

The Spacecraft Control Toolbox (SCT) was developed by Princeton Satellite Systems. SCT assists with designing, analysing, and simulating spacecraft trajectories [34]. SCT is widely used by spacecraft manufactures, and research and development institutions. It comprises over two thousand functions for attitude and orbit dynamics, simulation, estimation, analysis, and design. SCT also employs other graphical CAD tools for its visualisation capabilities. Furthermore, one can perform disturbance analyses and test the control systems in a six-degree-of-freedom simulation in a MATLAB environment.

SCT is proprietary software and is available in three editions: Professional; Academic; and CubeSat editions. The professional edition includes elaborate examples for designing spacecraft control systems. Add-on modules comprise fusion propulsion, formation flying, solar sails, launch vehicles, and spin-axis attitude determination in transfer orbits. Both the Academic and CubeSat editions are a subset of the Professional edition intended for graduate level control systems design and analysis, as well as an entry level product for CubeSat manufacturers respectively. In addition, SCT contains advanced tools for sensor and actuator modelling, subsystem analysis, orbit analysis, spacecraft trajectory designs, and attitude and orbit estimation. See reference [34] for more information on the key features of SCT.

2.3 Visualisation Tools for Space Mission Simulation

Visualisation tools aid in the mission planning and decision-making processes required for a successful space mission project. These tools are mostly a collection of COTS and sometimes Government-off-the-shelf (GOTS) artifacts [36] . They provide a mathematically correct, visually rich environment allowing for realistic simulation, presentation and evaluation of platform selection and flight profiles for mission planning. Visualisation tools can integrate information on spacecraft capabilities and mission specific objectives, which includes attitude manoeuvres, spacecraft trajectories, and the provision of accurate and timely information to meet mission objections. The goals of visualisation tools are mostly accomplished through approaches such as feasibility, variability, visibility and certainty [36]:

- Feasibility. This provides the knowledge to ascertain the success or accomplishment of a mission. It reflects on a mission by way of ground and space assets through line-of-sight tracking, providing analysis report for link margin and launch times meeting mission success criteria. Radar tracking stations, telemetry and telecommand stations and camera optics stations are some examples of ground-based assets.

- Variability. Ability to adjust various spacecraft mission characteristics to enhance the performance of the mission. For example, it helps in varying mission parameters to meet the required mission criteria by streamlining the variability-feasibility processes.
- Visibility. Provides visibility for missions in 2D and 3D environments. This includes, detailed, dynamic 3D models, high resolution imagery, launch trajectory, spacecraft trajectory, attitude information/data line-of-sight information, etc. Also, these 3D models aid in visualising launch payloads, multiple stage separation, sensor locations with a combination of analysis capabilities.
- Certainty. This offers accuracy in the calculated mission parameters through either the 2D or 3D representation. It helps in evaluating, verifying and validating mission certainty using comparative analysis in both pre- and post- flight analysis.

All of the space mission software described in Section 2.2 employ a visualisation tool as a critical component for mission design and performance analysis. In addition to the integrated visualisation solutions in package such as STK, Basilisk and PIGI, there are additional visualisation tools that are often utilised for space missions. We consider two of these solutions here: Caesium JS [36] and Celestia [37].

2.3.1 Cesium

Cesium was developed by aerospace software company Analytical Graphics Inc. in 2011 [38]. Cesium provides a fundamental open platform for an interoperable geospatial ecosystem, offering a mix of open source and commercially available software. The platform provides a complete suite of tools for building 3D geospatial applications of any kind (see Figure 9). Cesium has several platforms, from which the Cesium JS platform is most suitable for space mission visualisation.

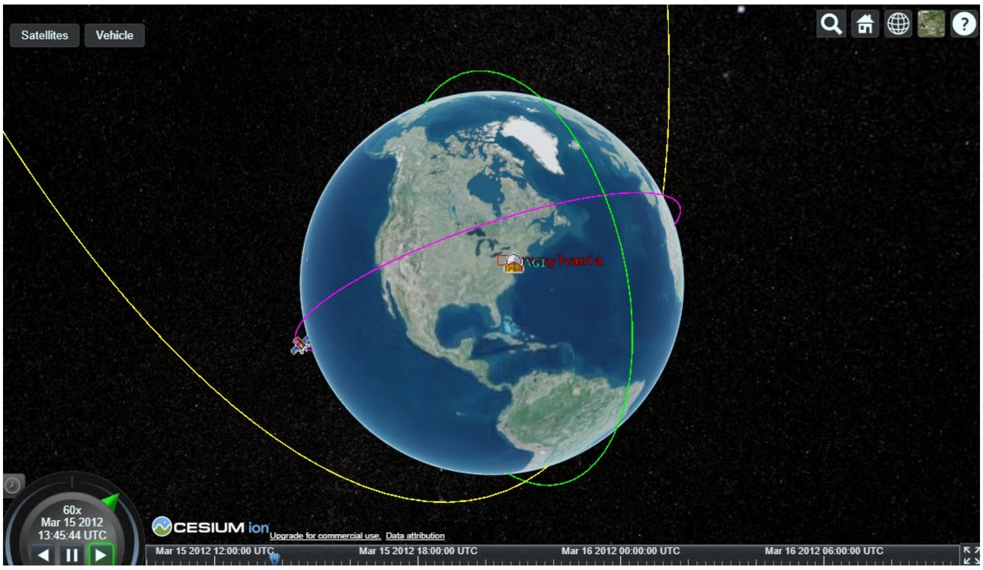


Figure 9. An example of the Cesium ion visualisation interface [36].

Cesium features include a JavaScript library for creating 3D geospatial visualizations that can execute in a browser and across devices, a high-precision WGS84 globe that supports accurate analytics, and a smooth user experience that scales for massive datasets (utilising streaming via 3D Tiles and other standard formats). These features are accessible via the Cesium ion cloud platform. Cesium is an open-source solution, except for the advanced analytics capabilities with Cesium ion Software Development Kit (SDK), which are subject to a licence [36].

2.3.2 Celestia

Celestia is a platform independent, open-source, 3D visualisation tool (see Figure 10). Primarily used by amateur astronomers and educators, it has been adopted for use in mission design and spaceflight visualisation [37]. Celestia's main aim is for visual realism, and thus it can simulate and represent different types of celestial objects. Celestia's input source catalogues can be expanded to include different add-ons as well as 3D models of spacecraft and trajectories. The position and movement of the solar system objects can be calculated accurately in real time at any rate desired.

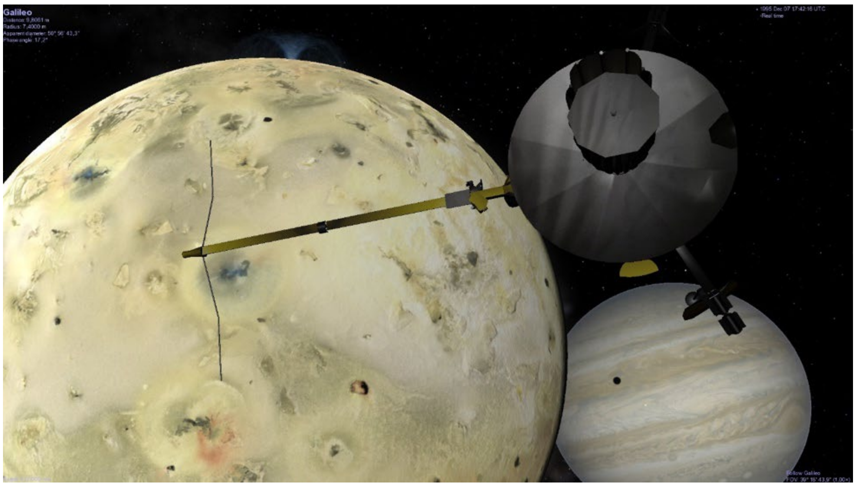


Figure 10. Celestia visualisation interface showing an encounter with Io.

3 Outcomes of User Engagement Process

The project team engaged with several SmartSat partners and end-users through informal interviews to better understand and establish specific needs for astrodynamics simulation and visualisation capabilities. This approach was used to both assist with the selection of simulation software for evaluation, based on solutions that were currently in use, and as an input to the development of metrics for evaluating spacecraft mission simulation software.

The interview comprised questions pertaining to:

- Level of use of simulation and visualisation software for space applications – day-to-day operations
- Best feature(s) and biggest limitation(s) for primary and secondary use cases
- Performance features – accuracy and effectiveness of simulation outputs
- Ease of usage – level of understanding of software package
- Requirements for updates
- Visualisation tools – user interface (fit for purpose?)
- Value for money
- Whether other astrodynamics simulation software had been considered
- Desirable characteristics for software that might meet demands for all space applications/operations.

3.1 User Consultation and Perspectives

The responses acknowledged the importance of astrodynamics software for space simulation and visualisation, which have become necessary for the day-to-day operations of most space industries. Australia is growing its sovereign capability in satellite design, launch, and operation, particularly through near-term activities such as the Kanyini Space Services Mission, the Resilient Multi-Mission Space STaR Shot program (Australian Defence Force) and National Space Mission for Earth Observation. As such, the need to perform "deep-seated" simulations (e.g. high fidelity simulations) and to analyse current patterns of spacecraft behaviour is critical for understanding the space environment in which these satellites will operate.

Some of the software mentioned included options that are described in Section 2 – STK, GMAT, Freeflyer, Orekit – along with more general-purpose data analysis or computation options such as MATLAB[1], DRAMA[2], GNU Octave[3], and Microsoft Excel. However, not all these solutions were currently being used: a common theme was the cost associated with proprietary solutions, which often grows more expensive with each iteration or changes to the software. Open-source software was favoured, but only if there was an option to utilise industry specific add-ons or plugins.

In terms of general features, there was a need for the useability of spacecraft simulation software to be improved, and the associated user documentation was not always sufficiently helpful (noting the range of experience present in different user cohorts). Additionally, while noting the importance that a simulation must provide valid results, the effectiveness of the software for specific use cases was assessed in terms of increasing accuracy, low risk performance, lower latency, higher responsiveness, improved run speeds and time saving. Some of the software was heavily disadvantaged in terms of their visualisation capabilities, usually because they were closed-sourced and hence restrictive (e.g. SCT).

Understanding a software package is vital for providing the desired results. In most cases, the software package is not straightforward for novice or occasional users, as it written by and for technical experts. Besides the requirement for on-going updates, it is also important to consider the potential for improvements and integration of new techniques or operational modes, for example support for modelling multi-spacecraft constellations. Such features are not currently supported by several the software packages, which are not easily adaptable to user-specific modifications because of their proprietary status. However, providing enhanced support systems and/or packages is important for improving the user's experience.

As reliance on astrodynamics software grows, so will the demand for improved support, integration, and appropriate user interface for easy learning. The visualisations tools accompanying such software should be accessible with new technologies (e.g. augmented or virtual reality) to empower users to explore or communication mission scenarios. This may include increasing end user confidence in purchasing proprietary software, as well as providing opportunities for the user community to provide meaningful feedback or to participate directly in the development of the software.

In terms of value for money, commercially licensed astrodynamics software was thought to be expensive. There are special cases for some training organisations (e.g. universities) to buy limited

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[1] https://au.mathworks.com/products/matlab.html
[2] https://sdup.esoc.esa.int
[3] https://octave.org

lower-cost educational licences, however, that can lead to scenarios where the tools that students are learning with are not the same as those that are being used by potential employers.

Fortunately, other options for astrodynamics software for specialised space applications or operations exist such as PIGI, Basilisk and ASTOS which have very low-cost licensing options or are free. Indeed, open-source astrodynamics software has become a valuable asset, as it can be adapted or customised for a variety of new or novel use cases. However, careful consideration should be made to avoid incorrect results or unnecessary duplication of effort.

The idea of having one solution that could meet the demands of all space applications was thought to be unrealistic, as there may be too many requirements for analysis, simulation, and visualisation in that no one software can realistically meet all the demands. However, a fusion of the different requirements and components may be achievable, perhaps through a modular approach, where different simulation and visualisation components or algorithms can be connected. STK was perceived to be capable of meeting most end user demands, since it was developed for space operations, mission planning and analysis, rendezvous, multi-spacecraft missions, etc., but the complexity and cost meant that end-users were not able to easily assess its capabilities for their own use cases and workflows.

TABLE 2. NON-TECHNICAL FACTORS IMPACTING CHOICE OF MULTI-SPACECRAFT MISSION SIMULATION AND VISUALISATION SOFTWARE

MMSV Software	Cost	Support for multi-mission operations?	Detailed training support? (Documentation)	Flexibility?
ASSET	Free	Yes	No	No
ASTOS	Medium	Partial	No	Yes
Basilisk	Free	Yes	Yes	No
Freeflyer	Medium	Yes	Yes	No
GMAT	Free	No	Yes	Yes
Orekit	Free	No	Yes	Yes
PIGI	Low	No	No	Yes
SCT	Medium	Partial	Yes	No
STK	High	Yes	Yes	No

3.2 Software Options

When assessing software options and packages in the context of their ability to simulate full spacecraft dynamics, it is important to identify how the dynamics are computed and the impact this has on the implementation's software architecture. During the end-user consultation, a list of the most used astrodynamics simulation and visualisation software was developed. An investigation of the features, attributes, and characteristics, based on specific requirements such as cost, support for multi-spacecraft mission operations, and availability of detailed training support (particularly in the form of user documentation) is presented in Table 2.

Also considered were factors such as the extent to which the software supports fast, modular, and scalable optimisation platform allowing for novel mission design and analysis like multi-spacecraft, multi-target trajectory optimization, enable improved mission design efficiency, access, mission life, and new mission architectures.

3.3 Lessons Learnt

The consultative interviews with SmartSat CRC partners and end-users raised several interesting ideas and concerns regarding the use of astrodynamics simulation and visualisation software. The key lessons and findings are summarised as follow:

1. The importance of MMSV software as the go-to option for high fidelity simulations and visualisation of space operations.
2. There is a need to understand the constraints of both the software and the problem to find a suitable, cost-effective solution (appropriate software needs).
3. The perceived high cost of commercial software, particularly STK, poses a great concern, hence free or cheaper options are preferred.
4. Proprietary licences pose a constraint to the flexible usage of MMSV software, hence newer developments, such as open-source options that provide sufficiently accurate results, are used.
5. FreeFlyer was identified as a preferred option for several end-users, although the majority of those consulted in the interview phase were yet to explore this software.
6. There is no “one stop shop” for MMSV software that includes all required or desirable application packages for space operations, although STK is perceived to have the highest overall capability.
7. Training documents are not easily understood by all types of end users.
8. Most software is tailored to specific existing applications of space operations hence may not be suitable for new industry project requirements.
9. Most of the options mentioned or investigated where limited in terms of their support for multi-spacecraft mission planning.
10. STK, GMAT, FreeFlyer were the three most well-known examples of MMSV software but were not necessarily in day-to-day use. Other options, such as PIGI, were thought to be of value, but there was limited understanding of its capabilities.

These findings suggest an opportunity to further understand the current needs of SmartSat CRC partners and end-users, including the importance of providing access to relevant options for individual assessment. This will help tailor the need for a future software architecture for space mission planning and operations for the Australian Space Industry.

4 Concluding Remarks

Astrodynamics simulation and visualisation software, tools and platforms have become an indispensable part of modern spacecraft design and mission operation processes. These simulation tools can provide end users, mission planners, and engineers with the ability to increase the quality of design and testing by reducing the cost and duration of development. For example, proposed changes to a mission's configuration, parameter tuning, or response to in-flight anomalies may be explored via simulation scenarios.

With the goal of advancing Australia's capabilities in multi-mission spacecraft simulation and visualisation, the study sought to provide improved understanding of: (i) the capabilities and usability of existing astrodynamical and mission simulation software; and (ii) the needs of SmartSat industry partners and end users.

Starting with an initial list of 21 different simulation and visualisation packages (Section 2, Table 1), including open source and proprietary options, we selected 10 options for further investigation. This down-selection was strongly informed by the outcomes of the SmartSat industry partner and end-user consultation processes (Section 3), which aided in the identification of non-technical features that influenced choices regarding adoption and use of software. We are grateful to the organisations that participated in this consultation process.

Our end-user consultation resulted in a set of lessons, with the most important outcomes related to three key barriers to up-take: (i) the actual, or perceived, high cost of proprietary licenses, leading to a preference for open source solutions that might not be as fully-featured as commercial alternatives; (ii) lack of appropriate training materials or documentation, meaning that the requirements for a spectrum of skill levels from novice to expert where not sufficiently well met; and (iii) insufficient flexibility in software, or combinations of software, that was currently being utilised in order to address individual industry-specific requirements.

While not a barrier to entry, for now, most of the options investigated where limited in terms of their support for multi-spacecraft mission planning and operations. Two of the toolkits investigated – FreeFlyer Astrodynamics Software (A.I. Solutions) and the Predictive Interactive Ground-Station Interface (PIGI; Saber Astronautics) – were found to provide the overall best fit to the criteria that they be relatively easy to use, accessible, cost effective, have good computational performance and provide appropriate visualisation outputs. Our examination of current astrodynamic simulation and visualisation software, combined with an improved understanding of the needs of industry partners and end-users, suggests that these two options may be the most amenable to adaptation for future research and development activities focusing on multi-spacecraft scenarios.

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