FreeFlyer® Independent Verification & Validation Summary

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Contents

1.0 Introduction

FreeFlyer® supports mission-critical functions in both manned and unmanned space flight segments. Independent verification and validation (IV&V) is an essential component to ensuring FreeFlyer's accuracy, reliability, quality, performance, and analytical fidelity. Many companies and agencies that purchase FreeFlyer choose to perform their own IV&V analysis. **a.i. solutions** wholly supports these efforts and will make documentation on them available where permissible. Additionally, a.i. solutions employs rigorous acceptance and regression testing methods to ensure that a high degree of confidence in the FreeFlyer software is maintained with each new FreeFlyer release.

1.1 Purpose

The purpose of this document is to provide a historical summary of cases where FreeFlyer has been verified by both independent entities and by a.i. solutions. Because a.i. solutions is also a provider of aerospace engineering and systems engineering services, a.i. solutions has, in the past, been contracted to provide analysis, integration, testing, and operational mission support using FreeFlyer. FreeFlyer is also used every day to support many operational on-orbit missions. Summaries of our integration and testing of FreeFlyer and FreeFlyer's use in support of operational on-orbit missions are provided in Sections 2.0 and 3.0 below.

1.2 Document Updates

This document will be updated at the discretion of a.i. solutions, Inc. and when necessary to maintain accuracy of information contained herein.

Revision	**Date**	**Updates**
1.0	08/2006	Initial Release
1.1	06/2009	Updates
2.0	06/2009	Added NASA/Robotic Collision Risk Assessment System
3.0	03/2010	Added Orbit Determination and Solid Tides Verification
3.1	01/2011	Updated list of Missions Supported; Added efforts for 2009-2010
3.2	03/2013	Added NASA JSC Evaluation of FreeFlyer against MONTE, SGSS, LDCM FreeFlyer Orbit Determination Analysis, ISSAAA Orbit Determination and Prediction, Bidder's Library Data Orbit Determination Study
3.3	05/2015	Added recent numerical validation studies and operational Orbit Determination support.
3.4	04/2019	Evaluated recent IV&V additions and changes to ensure that everything is accurate and up-to-date.
4.0	07/2020	Updated ISO/CMMI information and end dates of validation activities.

2.0 Verification and Validation

FreeFlyer verification and validation has been performed either for the sole purpose of IV&V, such as the one performed by Computer Sciences Corporation, or by customers who want to verify FreeFlyer for use as a tool for analysis or mission-critical operations. A summary of various FreeFlyer verification and validation efforts is provided in the following subsections.

2.1 Air Force SMC Numerical Validation of FreeFlyer

Testing Entity:	Air Force SMC and A9/a.i. solutions
Date:	2012 – 2015
Testing Description:	Numerical validation of FreeFlyer IOD, Batch Least Squares OD, and TLE Generation against legacy operational tools. Testing coverage includes many satellites in all Earth-centered orbit regimes: LEO, MEO, GEO, and highly elliptic orbits.
Functions Validated:	• NORAD TLE element set conversions and propagation • Initial OD • Batch Least Squares OD • Ground-based Range and angles processing • Ground- and Space-based optical angles processing • NORAD TLE Generation

2.2 NASA JSC Evaluation of FreeFlyer against MONTE

Testing Entity:	NASA JSC	
Date:	2012 – 2014	
Testing Description:	The core astrodynamics functionalities of FreeFlyer are being evaluated against the Jet Propulsion Laboratory (JPL) Mission-analysis, Operations, and Navigation Toolkit Environment navigation program (MONTE).	
Functions Validated:	**Complete** • Time conversions • Coordinate transformations • Force models (gravitational, drag, solar radiation pressure)	**Ongoing** • Trajectory propagation • Maneuver modeling • Measurement processing • Estimation

2.3 Verification of FreeFlyer's Orbit Propagation and Maneuver Targeting

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2012 – Present
Testing Description:	An evaluation of FreeFlyer will be conducted in support of the SN Ground Segment Sustainment (SGSS) program. Orbit propagation results will be verified against data from the legacy software being used to operate the TDRS (WSC) and data from the Flight Dynamics Facility (FDF), flight dynamics products generation (including eclipses, look angles, and radio frequency interference) will be compared against WSC data, maneuver targeting (station-keeping maneuvers, station change maneuvers, momentum unload maneuvers, and decommissioning maneuvers) will be compared against WSC data.
Functions Validated:	• Batch Least Squares OD • Bilateral Ranging Transponder System (BRTS) processing • Orbit propagation • Finite Burns

2.4 GMAT Evaluation of FreeFlyer

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2010 – Present
Testing Description:	Tests are conducted for spacecraft propagation, force model validation (including custom gravity models), maneuvering including both impulsive and finite burns, ephemeris generation, and vector validations as part of NASA's General Mission Analysis Tool (GMAT) Project.
Functions Validated:	• Spacecraft propagation • Force model validation • Impulsive burn • Finite burn • Ephemeris generation

2.5 *Replacement of GPS LADO Orbit Determination System with FreeFlyer*

Testing Entity:	The Boeing Company/a.i. solutions
Date:	2010 – 2012

Testing Description:	Initial Orbit Determination (OD) and Batch Least Squares OD results were verified against the operational GPS (Global Positioning System) LADO (Launch Anomaly and Disposal Operations) tools, CCS (Command & Control Segment) and Braxton ACE ADE, for the Mission Planning Consolidation project. Ground station observations including range, azimuth, and elevation measurements are used to solve for state, vehicle parameters, thrust events, and ground station parameters.
Functions Validated:	• Batch Least Squares OD • Impulsive Maneuver Estimation • Finite Burn Maneuver Estimation

2.6 Verification of FreeFlyer Propagation and Force Models for Libration Point Orbits

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2010 – 2012
Testing Description:	Station keeping and mid-course correction maneuvers were calculated for libration point orbiting spacecraft (ACE, Wind, and SOHO), modeling both impulsive and finite burns. Results are compared with the legacy software Swingby currently in use at GSFC. All parameters tested by FreeFlyer match those of Swingby to such a high degree that any differences between the values were deemed negligible for all mission planning purposes. Force model tested: 8x8 Earth geopotential model, gravitational influence from Sun, Moon, Venus, Mars, Jupiter, Saturn, Uranus, Neptune. Solar radiation pressure (SRP) on; no atmospheric drag. Propagator: Runge Kutta 8(9) integrator with various fixed step sizes (mainly 1000 s and 3000 s).
Functions Validated:	• Solar radiation pressure modeling • Gravitational force modeling with multiple celestial bodies • Orbit propagation • Extended ephemeris generation (up to 4 years) • Impulsive burn calculation • Finite burn calculation (including burn duration, fuel mass depletion, and fuel tank pressure drop) • Custom Vectors and Coordinate Systems

2.7 Verification of FreeFlyer MLTAN Algorithms

Testing Entity:	NASA Kennedy Space Flight Center/a.i. solutions

Date:	2010
Testing Description:	Mean local time of the ascending node (MLTAN), right ascension of the ascending node (RAAN), and Greenwich hour angle (GHA) calculations were verified against MATLAB™ scripts and the Multiyear Interactive Computer Almanac (MICA). These are important for mission design of sun-synchronous, repeating ground track, and other types of mission orbits that must satisfy Sun-orbit plane and other lighting constraints.
Functions Validated:	• Mean local time and GHA calculations • Motion of celestial bodies • Sun-synchronous orbit wizard

2.8 Verification of FreeFlyer Eclipse Pattern and Node Drift

Testing Entity:	Naval Research Laboratory
Date:	2010
Testing Description:	Eclipse pattern and node drift for a variety of injection conditions for the JMAPS (Joint Milli-arcsecond Pathfinder Survey) program were verified against STK® (Satellite Took Kit). Force models tested: High order gravity models with lunar and solar perturbations.
Functions Validated:	• Gravitational force modeling • Extended orbit propagation (3+ years)

2.9 Verification of FreeFlyer Kalman Filter using GPS Point Solution Data

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2010
Testing Description:	FreeFlyer was used to process about 5 hours of simulated GPS Point Solution data using a Kalman Filter, both with and without a Smoother. No a priori vector was supplied, so the GPS Point Solution data was used as the initial state source. The analysis was done in parallel with the NPP (NPOESS Preparatory Project) MOC (Mission Operations Center) in Suitland, MD. The NPP MOC uses a newly developed flight dynamics system called OO developed by Raytheon. FreeFlyer, OO, and ODTK® (Orbit Determination Tool Kit) were used to process the same set of data. The results, a single solution vector at a specified time near the beginning of the data, matched ODTK within 3 meters and matched OO within 20 meters.
Functions Validated:	• Kalman Filter OD • Kalman Smoothing

	• GPS Point Solution processing

2.10 LDCM FreeFlyer Orbit Determination Analysis

Testing Entity:	a.i. solutions
Date:	2009 – 2012
Testing Description:	An evaluation of FreeFlyer's Orbit Determination solution was conducted for the Landsat Data Continuity Mission (LDCM). FreeFlyer's position, velocity, and coefficient of drag estimates of flight data from the Fermi Gamma-ray Space Telescope (FGST) were compared against the filtered and smoothed solution from Orbit Determination Took Kit (ODTK). FreeFlyer's solution was also validated against four sample sets of Spacecraft/Operations Simulator (S/OS) Telemetry data.
Functions Validated:	• Kalman Filter OD • GPS Point Solution processing

2.11 Verification of FreeFlyer Propagation and Force Models

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2009 – 2011
Testing Description:	Long-term propagations and mean local time predictions were compared to definitive ephemerides over a 10-month time span for an orbit with a 705 km equatorial altitude. Force model tested: 30x30 geopotential with 2x2 solid tide model and permanent tides, SRP, drag, and Sun/Moon point masses. Jacchia Roberts atmospheric model used with the latest NOAA solar predictions from the GSFC FDF. Propagator tested: Runge Kutta 8(9) integrator with a 60 second step size.
Functions Validated:	• Solid tide modeling • Gravitational and atmospheric force modeling • Orbit propagation

2.12 *Verification of FreeFlyer Propagation and Orbit Events*

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2009

Testing Description:	Day/night crossing times and ground station AOS/LOS (acquisition and loss of signal) times were used to verify STK products delivered to the FOT (Flight Operations Team) during the 2009 Aqua and Aura inclination maneuver series.
Functions Validated:	• Orbit propagation • Orbit events

2.13 Verification of FreeFlyer's Orbit Determination and Ephemeris Prediction using ISSAAA Data

Testing Entity:	a.i. solutions/AF/AFSPC/SMC
Date:	2008, 2010
Testing Description:	An evaluation of FreeFlyer's orbit determination and propagation algorithms was conducted. SSN data for the CHAMP satellite was processed and compared against SLR-based solutions generated by JPL.
Functions Validated:	• Batch Least Squares OD • Kalman Filter OD • Spacecraft Propagation • Ground-based Range and angle processing

2.14 Verification of FreeFlyer Gravity and Solid Tide Models

Testing Entity:	a.i. solutions
Date:	2008
Testing Description:	FreeFlyer propagation results are compared to GTDS (Goddard Trajectory Determination System) results. Force models tested: Earth point mass; Earth/Moon/Sun point masses; JGM-2 4x4, 21x21, 22x22, 30x30, and 40x40; and JGM-2 30x30 with Solid Tides.
Functions Validated:	• Solid tide modeling • Gravitational force modeling • Orbit propagation

2.15 ISS Flight Following with Temporis/FreeFlyer

Testing Entity:	United Space Alliance

Date:	2008
Testing Description:	FreeFlyer is the astrodynamics system-integration engine for Temporis™, the United Space Alliance spaceflight mission management and planning tool. The FreeFlyer component provides trajectory and attitude ingest capabilities, power modeling, communications modeling, visualization products, and a daily orbit tracker product. The Temporis system was tested during a Benchmarking Demonstration which included ISS Flight Following and Proof of Concept on Actual ISS Data.
Functions Validated:	• Orbit and attitude ingest • Power and communications modeling • 2D and 3D visualization

2.16 Testing of the Java Astrodynamics Toolkit Propagator against FreeFlyer and STK

Testing Entity:	Emergent Space Technologies
Date:	2006
Testing Description:	Earth orbit ephemerides were created using the Java Astrodynamics Toolkit (JAT), STK/HPOP (High Precision Orbit Propagator), and FreeFlyer 5.5.0.25. Sun-synchronous, geostationary, Molniya, ISS, and GPS orbits were used. Results showed agreement of millimeter to meter level over several days. Force models tested: Two-body Earth gravity, JGM-2, Solar/Lunar third-body effects; atmospheric drag using the Harris-Priester density model; and SRP Propagator tested: Runge Kutta 8(9) integrator with a variety of step sizes, durations, and output frequencies.
Functions Validated:	• Gravitational force modeling • Orbit propagation

2.17 Integration of FreeFlyer into the NASA/CARA System

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2005 – 2007
Testing Description:	The FreeFlyer component of the NASA/CARA System is used to determine close approach times, miss distances, and collision probability values. These calculations are compared to those

	provided by operators at the Joint Space Operations Center (JSpOC) at Vandenberg AFB. Risk Assessment analysis is performed using the output from these FreeFlyer utilities.
Functions Validated:	• Collision avoidance maneuver planning • Orbit propagation • Time of Closest Approach Determination

2.18 Verification of FreeFlyer Propagation and Force Models for GPS

Testing Entity:	The Boeing Company/a.i. solutions
Date:	2005 – Present
Testing Description:	FreeFlyer was tested against the GPS IIF Simulator, STARSim. Orbit propagators were tested with Earth, Sun, Moon, and SRP models.
Functions Validated:	• Orbit propagation • ASCII/binary file interface • Attitude model

2.19 *Verification of the FreeFlyer Orbit Determination System*

Testing Entity:	a.i. solutions
Date:	2004 – Present
Testing Description:	Both ground-based and space-based solutions were validated using Aqua flight data against ephemerides generated from other tools (RTOD (Real Time Orbit Determination)/GTDS). Point Solution results were validated using flight data from GLAST against an ephemeris generated by ODTK. Pseudorange solutions were validated using SAC-C data against JPL solutions generated with GIPSY-OASIS II.
Functions Validated:	• Orbit determination

2.20 Integration of FreeFlyer into the EOS Aura Flight Dynamics System

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2004
Testing Description:	The FreeFlyer component of the EOS (Earth Observing System) Aura Flight Dynamics System was tested against the operational Aqua Flight Dynamics System and the requirements levied against the Aura Flight Dynamics Team and specifications as outlined in the

	Aura Interface Control Documents (ICDs). Aura-unique requirements were verified using MATLAB, STK, and in-house tools.	
Functions Validated:	• Maneuver targeting • Maneuver planning • Coverage analysis	• Orbit propagation • Orbit events

2.21 *Replacement of Legacy CCS Maneuver Planning System for GPS LADO with FreeFlyer*

Testing Entity:	US Air Force/The Boeing Company
Date:	2003 – Present
Testing Description:	FreeFlyer was tested against the legacy/operational CCS Maneuver Planning System for GPS LADO using historical operations cases and compared to off-line/backup Orbit Analyst (OA) GPS analysis tools. Orbit and attitude maneuvers used to ascend a GPS satellite from launch insertion to on-station were calculated in FreeFlyer and compared against operational maneuvers that were actually performed. States were acquired from the GPS operational area at Schriever AFB from the IIA and IIR families of operational GPS satellites.
Functions Validated:	• Maneuver targeting ◦ Spin precession ◦ AKM (Apogee Kick Motor Maneuver) ◦ De-spin ◦ Translational (i.e. orbit adjust) • Maneuver planning • Orbit propagation • MATLAB interface • Database interface • TCP/IP socket interface • Multi-spacecraft (i.e. constellation modeling) • ASCII/binary file interface • Orbit events • Attitude model • Sensor model • Coverage analysis

2.22 Verification of FreeFlyer Bi-Propellant Engine Model

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2003
Testing Description:	The FreeFlyer bi-propellant engine model was tested against the bi-propellant engine model in NASA's General Maneuver (GMAN) software.
Functions Validated:	• Bi-propellant engine model • Tank modeling • Thruster modeling

2.23 Verification of FreeFlyer Close Approach Algorithm

Testing Entity:	NASA Goddard Space Flight Center/a.i. solutions
Date:	2003
Testing Description:	The FreeFlyer implementation of the *Alfano-Negron Close Approach Software* (ANCAS) algorithms was verified against a MATLAB simulation and against the STK/Collision Avoidance Tool (CAT).
Functions Validated:	• Close approach • Monte Carlo analysis

2.24 Verification of FreeFlyer Orbit Determination and Orbit Prediction for Real-Time Operations

Testing Entity:	US Army Space Command (ARSTRAT)
Date:	2001
Testing Description:	FreeFlyer received tracking data from the Army Space Command tracking terminals. FreeFlyer then determined and propagated states, which were compared to states generated by the 3 SOPS facility using the AFSCN network. Multiple test cases were performed using the DSCS satellite in orbit.
Functions Validated:	• Orbit determination • Orbit propagation • Error analysis

2.25 Independent Verification and Validation

Testing Entity:	Computer Sciences Corporation (CSC)

Date:	2001	
Testing Description:	Ninety-seven tests were performed, validating FreeFlyer against several commercial software tools including STK/Pro, STK/Astrogator, and MATLAB and several NASA tools including the General Maneuver (GMAN) utility, the Goddard Mission Analysis System (GMAS), Acqscan, and Swingby.	
Functions Validated:	• Orbit propagation • Orbit events • Fuzzy logic • Maneuver targeting • Force modeling • TCP/IP sockets • Reporting & plotting	• 3D visualization • Coordinate systems • Station coverage • Monte Carlo analysis • MATLAB interface • Drag model

2.26 COTS Evaluation for the Resource-21 Satellite Ground Control Center CPF

Testing Entity:	The Boeing Company	
Date:	1998	
Testing Description:	A series of tests were performed to evaluate several COTS (Commercial Off The Shelf) products for the Resource-21 Satellite Ground Control Center, Central Processing Facility (CPF). FreeFlyer functionality and test results were compared to Boeing in-house tools.	
Functions Validated:	• External interfaces • Orbit propagation • Orbit events • Ephemeris generation • Coordinate systems	• Maneuver planning • Maneuver targeting • Station-keeping • Antenna model • Coverage analysis

3.0 Sample of Operational Mission Support

FreeFlyer has been used to support over 225 civil (NASA, NOAA), DoD (MDA, US Air Force, US Army), and international customers for pre-mission analysis, early-orbit IV&V, and on-station operations. A *sample* of on-orbit missions that use FreeFlyer for daily operations and the FreeFlyer functionality they exercise is given below. Please note that due to the secure nature of some DoD programs, a.i. solutions is unable to provide information related to their FreeFlyer use.

<table>
<tr><td>CALIPSO, CloudSat</td><td>• Collision avoidance
• Orbit propagation
• MATLAB interface
• Database interface
• TCP/IP Sockets
• Automated parametric studies</td><td rowspan="6">SDO</td><td rowspan="6">• 2D and 3D visualization
• Real-time attitude determination
• Batch attitude determination
• High Gain Antenna (HGA) pointing calibration
• Sun sensor calibration (FOV alignment and bias determination)
• Orbit and mission products generation
• Link margin calculations/products
• Ascent to GEO maneuver planning
• Burn calibration (complete propulsion system modeling for bi-propellant and blow-down configurations)
• Station-keeping maneuver planning
• Command file generation
• Fully automated to support “lights-out” operations</td></tr>
<tr><td>DSCS</td><td>• Orbit determination</td></tr>
<tr><td>EOS Aqua/ Aura/ Terra</td><td>• Collision avoidance
• Orbit propagation
• Maneuver targeting
• Maneuver planning
• Coverage analysis
• Orbit events</td></tr>
<tr><td>GPS</td><td>• Orbit propagation
• Maneuver planning
• Maneuver targeting
• TCP/IP Sockets
• Database interface
• MATLAB interface
• Attitude determination system
• Binary/ASCII file interface
• Attitude history file
• Sensor model</td></tr>
<tr><td>LandSat 7</td><td>• Maneuver planning
• Orbit propagation
• Orbit events</td></tr>
</table>

3.1 *List of Missions Supported*

A sample of missions that use FreeFlyer for both analysis and operations is given below, along with the agency/customer for that mission.

Customer	Mission
Air Force Research Laboratory (AFRL)	ANGELS DSX
Boeing	1 SOPS Operations Center 2 SOPS Operations Center SBSS
CISCO	IP/Space
CNES	PARASOL
DLR (German Aerospace Center)	TanDEM-X TerraSAR-X
ISA (Italian Space Agency)	Malindi Tracking Station (Kenya)
NASA	ACE AIM ACRIMSAT ARTEMIS Astro-H/SXS CALIPSO CEV CHAMP CloudSat Constellation DART DAWN EFT-1 EO-1 EOS Aqua EOS Aura EOS Terra FAST GALEX GENESAT GLAST (FGST) Glory GPM GRACE 1 & 2 Gravity Probe B HINODE HST IBEX ICESat IMAGE ISS Jason-1 Jason-2/OSTM JIMO JWST Landsat-5 Landsat-7 LandSat-8 (LDCM) LRO MAP MESSENGER MMS MRO MSL Phoenix Polar QUIKSCAT RHESSI RBSP RXTE SAC-C SAMPEX SciSaT SDO SIRTF SOHO SORCE SpaceTech-5 (ST-5) STEREO A & B STS SUZAKU SWAS SWIFT TDRSS THEMIS A-E TIMED TOPEX TRACE TRMM WIND WISE WMAP
JAXA	ALOS
NOAA	DSCOVR GOES-I (8) GOES-J (9) GOES-K (10) GOES-L (11) GOES-M (12) GOES-N (13) GOES-O (14) GOES-P (15) NOAA-K (15) NOAA-L (16) NOAA-M (17) NOAA-N NOAA-N' NPP
Missile Defense Agency	NFIRE STSS STSS ATRR STSS Demo
Naval Research Laboratory	TacSat4
Orbital Sciences Corporation	Classified Missions
Raytheon	Classified Missions
Space Applications Services	PREMIER
Turkish Aerospace Industries (TAI)	Göktürk-1
US Air Force	JSpOC Mission System (JMS)
	GPS IIA-3 GPS IIR-11 GPS IIR-17 (M4)

Customer	Mission		
	GPS IIA-4 GPS IIA-8 GPS IIF-1 GPS IIF-2 GPS IIR-10	GPS IIR-12 GPS IIR-13 GPS IIR-14 (M1) GPS IIR-15 (M2) GPS IIR-16 (M3)	GPS IIR-18 (M5) GPS IIR-19 (M7) GPS IIR-20 (M6) GPS IIR-21 (M8)
US Army (ARSTRAT/SMDC)	DSCS		
Other R&D	DLR Institute for Defense Analyses Naval Research Laboratory Northrop Grumman Aerospace Systems Oceaneering International Orbital Sciences Corporation	Raytheon Space Applications Services SRI International ISTI (Italy) United Space Alliance US AFRL (Air Force Research Laboratory)	

3.2 Sample of Maneuver Support

The table below provides a sample of maneuver types and missions that have been supported using FreeFlyer. Over 600 maneuvers have been supported by FreeFlyer at NASA GSFC alone.

Maneuver Type	Missions Supported
Ascent/Orbit Raise	Aura, Aqua, Terra, EO-1, GPS IIR, SDO, LDCM
Geosynchronous Station-keeping	GOES N-P, TDRS, SDO
LEO Orbit Maintenance (DMU)	Aqua, Aura, Terra, GPM, TRMM, EO-1, Landsat-5, Landsat-7, LDCM
Inclination Maintenance	Aqua, Aura, Terra, LDCM
Momentum Dumping	GOES N-P, TDRSS
Collision Avoidance	Aqua, Aura, Terra, CloudSat, PARASOL, EO-1, LDCM, ISS
Deorbit/Disposal Operations	ERBS, SDO, GPM, GPS IIA, GPS IIR, LDCM
Yaw Flip	TRMM
Precession Maneuver	GPS IIR
Libration Point Station-keeping	ACE, WIND, SOHO

3.3 Sample of Orbit Determination Support

The table below provides a sample of how FreeFlyer's Orbit Determination capabilities have been used for both analysis and operations.

Mission	Date	Description
JSpOC Mission System (JMS)	2015-Present	Initial OD, Batch Least Squares OD and NORAD TLE Generation in support of Breakup and Launch Services, processing ground- and space-based SSN tracking data.
ISS	2015-Present	Real-time Kalman Filtering of GPS Point Solution Data.
ANGELS	2014-Present	Batch Least Squares and Kalman Filter OD processing AFSCN tracking data.
Raytheon	2014-Present	Orbit Determination and maneuver planning for a classified mission.
SGSS	2012 - Present	Orbit Determination solutions using Batch Least Squares OD processing TT&C and BRTS range data.
GPS LADO	10/2010 – 2012	Processing ground station observations as part of the Mission Planning Consolidation effort for the GPS LADO ground system.
NPP	4/2010	Processing Point Solution data in a Kalman Filter with and without Smoother as part of a verification effort for the NPP MOC.
MMS	2/2010	Study on Smoothing to improve a post-maneuver ephemeris.
SBSS	2009 - Present	Batch Least Squares processing of GPS Point Solution data as part of the SBSS ground system.
LDCM (LandSat-8)	2009 - Present	Kalman Filtering GPS Point Solution and Pseudorange (TBD) data as part of the LDCM ground system.
ISSAAA - AFSPC/SMC	8/2008-10/2008, 4/2010-5/2010	Study to process SSN data and compare against SLR-based solutions.
NASA JSC	2008 - Present	Pre-flight mission analysis, data simulation for lunar and cis-lunar orbits using both Batch and Kalman Filter OD.
General Dynamics	Operations: 9/2005 - Present	GPS Point Solution and AFSCN ground station tracking data used for NFIRE and 2 other classified missions.
ARSTRAT	Development: 2001-2004, Operations: 2003-2009	Real-time operational Kalman Filter orbit determination of ground station observations and event prediction system developed in support of payload operations at Schriever AFB for various satellites in the DSCS constellation.

3.4 Expendable Launch Vehicle (ELV) Programs Supported with FreeFlyer

FreeFlyer has been in use by the NASA Kennedy Space Center Expendable Launch Vehicle (ELV) office since 1998. FreeFlyer has supported a variety of ELV programs including Pegasus XL, the Atlas fleet, the Delta fleet, and the Titan fleet. FreeFlyer is used to perform a wide range of analyses including:

- analysis on mission-unique requirements
- lifetime studies (long term orbit propagation)
- trajectory analysis
- orbital debris analysis
- launch window analysis
- station coverage
- shadow times analysis
- sun angle monitoring
- exclusion zone verification
- trim correction maneuver (TCM) calculation
- Monte Carlo analysis on launch vehicle (LV) covariance
- launch covariance
- beta angle evolution
- mobile asset location determination
- relative motion studies (for multi-spacecraft launch)
- backwards propagation to determine debris origination points
- International Space Station (ISS) Collision Avoidance (COLA) probability analysis
- separation pointing requirements

4.0 Compliance and Certifications

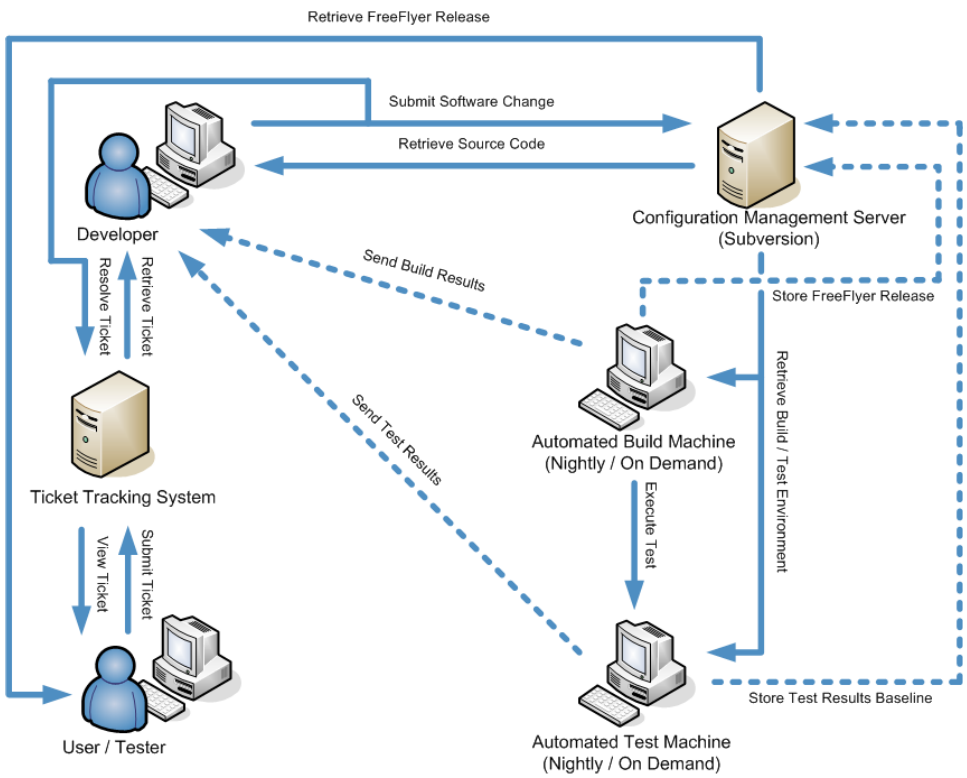
4.1 Certification to ISO 9001:2015 and AS9100-Rev D Standards

a.i. solutions is currently certified to the ISO 9001:2015 International Standard and AS9100-Rev D aerospace industry standard. ISO 9001:2015 requires the organization to establish, document, implement, and maintain a quality management system and continually improve its effectiveness. AS9100-Rev D is an extension to ISO 9001, but with additional requirements that are essential to maintain the safety, reliability, and quality of aerospace products.

Configuration Management and Automated Regression Testing

As mandated by the ISO 9001:2015 AS9100-Rev D Standard, a.i. solutions maintains a configuration management (CM) process for software development and testing and monitors compliance through internal audits. During all phases of development, a.i. solutions uses a Software Configuration and Change Management (SCCM) tool to maintain version history of all software components.

The figure below shows a schematic of the FreeFlyer Automated Regression Test Process. FreeFlyer testers submit trouble tickets to the tracking system. Developers submit software changes to the CM server. An automated build process occurs nightly, test results are compared to baseline expected results, test summary reports are generated, and reports are emailed to the developers and testers. In the event of a discrepancy, trouble tickets are created and assigned to developers. After testing confirms that the issue has been addressed, trouble tickets are stamped as resolved and testers can view the updated ticket. This cycle repeats until a final build of FreeFlyer is released. This completely automated system allows a.i. solutions to validate a wide range of system changes, from a single configuration update to the integration of multiple changes.



4.2 Conformance of FreeFlyer to CMMI-DEV L3 Practices

a.i. solutions is also applying CMMI-Dev best practices for software and systems development. CMMI-Dev encourages process improvement for design, development, and delivery of the organization's products and services. a.i. solutions is appraised as a CMMI for Development Maturity and capability Level 3 organization (CMMI-DEV ML3) as of January 2018.

4.3 Conformance of FreeFlyer to the AFSPC160-102 Standard

A detailed analysis of the Air Force Space Command AFSPCI60-102 specification was performed by a.i. solutions in 2005. FreeFlyer's compliance with the AFSPCI60-102 specification and its successful support of missions within the DoD is documented in Reference 2.

4.4 FreeFlyer in DSS Certified Environments

FreeFlyer is currently used by the Boeing Corporation in a DSS (Defense Security Service) certified environment for the Space Based Space Surveillance (SBSS) Program.

Another government contractor has successfully requested to use and install FreeFlyer in a Sensitive Compartmented Information Facility (SCIF) governed by DSID 6/3. The contractor was required to submit a Software Evaluation Request Form (SERF) to the US Government in order to receive approval to install FreeFlyer.

In both of the above cases, the customer was required to request permission to install FreeFlyer.

5.0 Reference Documents

This section provides a list of relevant or referenced documents.

Reference 1 “Testing of the Java Astrodynamics Toolkit Propagator”, *Emergent Space Technologies*, D. Gaylor, R. Page, K. Bradley, August 2006

Reference 2 “FreeFlyer® Support of Department of Defense Programs”, *a.i. solutions*, inc., August 2005

Reference 3 “EOS Aura Flight Dynamic System (FDS) Software Acceptance and Regression Test Plan”, NASA Goddard Space Flight Center, July 2004

Reference 4 “Solar Dynamics Observatory (SDO) Solar Dynamics Observatory (SDO) Comparison of Maneuver Modeling in GMAN and FreeFlyer®”, *a.i. solutions*, R. McIntosh, December 2004

Reference 5 “FreeFlyer® Verification and Validation Setups, Results, and Summary”, Computer Sciences Corporation, June 2001

Reference 6 “Resource-21 Orbit COTS Evaluation”, Boeing Arizona Operations Space & Communications, *Boeing Proprietary,* S. Sponaugle, D. Kirkpatrick

Reference 7 “Addendum to Orbit Determination and Prediction Evaluation”, *MITRE*, L. Grimaldi, July 2010.

Reference 8 “LDCM FreeFlyer Orbit Determination Analysis”, *a.i. solutions*, inc, A. Nicholson & L. Chung, April 2012

Reference 9 “Numerical Validation Phase I-A Report”, *Aerospace Corporation, MITRE*, JMS NumVal Working Group, Jun 2013.

Reference 10 “Independent Verification & Validation of JSC MOD Trajectory Software”, *NASA JSC,* May 2014

Reference 11 “FreeFlyer vs. Swingby: A Performance Comparison for Libration Point Orbit Stationkeeping Maneuvers”, *a.i. solutions*, M. Shouppe, Dec 2010