U.S. Department
of Transportation
**Federal Aviation
Administration**

Advisory Circular

Subject: Trajectory Analysis for Normal Flight

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Initiated By: AST-1

AC No: 450.117-1

This advisory circular (AC) provides guidance and a comprehensive method for performing a normal trajectory analysis in accordance with § 450.117, *Trajectory Analysis for Normal Flight*, of title 14 of the Code of Federal Regulations (14 CFR). This AC assists with performing a trajectory analysis for normal flight. A normal trajectory analysis includes trajectories that characterize the nominal trajectory, as well as both variability and uncertainty per § 450.117(a), using a 6 degree of freedom trajectory model per § 450.117(b), and account for atmospheric conditions, per § 450.117(c). This AC also provides guidance for an operator that chooses to propose a means of compliance for the requirements found in § 450.117.

The Federal Aviation Administration (FAA) considers this AC a means of compliance for complying with the regulatory requirements of § 450.117. It presents one, but not the only, acceptable means of compliance with the associated regulatory requirements. The contents of this document do not have the force and effect of law and are not meant to bind the public in any way. The document is intended only to provide clarity to the public regarding existing requirements under the law or agency policies.

If you have suggestions for improving this AC, you may use the Advisory Circular Feedback form at the end of this AC.

WAYNE R MONTEITH Digitally signed by WAYNE R MONTEITH
Date: 2021.08.19 17:01:40 -04'00'

Wayne Monteith
Associate Administrator
Commercial Space Transportation

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1 PURPOSE.

This advisory circular (AC) provides guidance and a comprehensive method for performing a normal trajectory analysis in accordance with § 450.117 of title 14, Code of Federal Regulations (14 CFR). A normal trajectory analysis is a required component of a flight safety analysis (FSA), per § 450.117(a). As such, the requirements of § 450.115 are applicable to the trajectory analysis developed under § 450.117.

1.1 **Analysis Scope**.

In accordance with § 450.115(b)(1), an FSA must demonstrate that any risk to the public satisfies the safety criteria of § 450.101, including the use of mitigations, and account for all known sources of uncertainty, using a means of compliance accepted by the FAA Administrator. In accordance with § 450.101(g), for any analysis used to demonstrate compliance with § 450.101, an operator must use accurate data and scientific principles. Also, the analysis must be statistically valid. Also, in accordance with § 450.101(g), the method must produce results consistent with or more conservative than the results available from previous mishaps, tests, or other valid benchmarks, such as higher-fidelity methods.

1.2 **Description of Methods**.

To satisfy the requirements of § 450.115(c), an applicant must submit a description of the flight safety analysis methodology, including identification of:

- The scientific principles and statistical methods used;
- All assumptions and their justifications;
- The rationale for the level of fidelity;
- The evidence for validation and verification required by § 450.101(g);
- The extent to which the benchmark conditions are comparable to the foreseeable conditions of the intended operations; and
- The extent to which risk mitigations were accounted for in the analyses.

1.3 **Level of Imperatives**.

This AC presents one, but not the only, acceptable means of compliance with the associated regulatory requirements. The FAA will consider other means of compliance that an applicant may elect to present. Other means of regulatory compliance may be acceptable, but must be approved by the Administrator in accordance with § 450.35(b). In addition, an operator may tailor the provisions of this AC to meet its unique needs, provided the changes are accepted as a means of compliance by the Administrator. Throughout this document, the word “must” characterizes statements that directly follow regulatory text and therefore, reflect regulatory mandates. The word “should” describes a requirement if electing to use this means of compliance; variation from these requirements is possible, but must be justified and accepted by the FAA as an alternative means of compliance. The word “may” describes variations or alternatives allowed within the accepted means of compliance set forth in this AC. In general, these alternative approaches can be used only under certain situations that do not compromise safety.

2 APPLICABILITY.

2.1 The guidance in this AC is for launch and reentry vehicle applicants and operators applying for a license under part 450. The guidance in this AC is for those seeking a launch or reentry vehicle operator license, and a licensed operator seeking to renew or modify an existing vehicle operator license.

2.2 The material in this AC is advisory in nature and does not constitute a regulation. This guidance is not legally binding in its own right and the FAA will not rely upon this guidance as a separate basis for affirmative enforcement action or other administrative penalty. Conformity with this guidance document (as distinct from existing statutes and regulations) is voluntary only, and nonconformity will not affect rights and obligations under existing statutes and regulations. It describes acceptable means, but not the only means, for demonstrating compliance with the applicable regulations. The FAA will consider other means of compliance that an applicant may elect to present.

2.3 The material in this AC does not change or create any additional regulatory requirements, nor does it authorize changes to, or deviations from, existing regulatory requirements.

3 APPLICABLE REGULATIONS AND RELATED GUIDANCE DOCUMENTS.

3.1 Related U.S.C. Statute.

- 51 U.S.C. Subtitle v, chapter 509.

3.2 Related FAA Commercial Space Transportation Regulations.

The following 14 CFR regulations must be accounted for when showing compliance with 14 CFR § 450.117. The full text of these regulations can be downloaded from the U.S. Government Printing Office e-CFR. A paper copy can be ordered from the Government Printing Office, Superintendent of Documents, Attn: New Orders, P.O. Box 371954, Pittsburgh, PA, 15250-7954.

- Section 401.5, *Definitions*.
- Section 450.35, *Means of Compliance*.
- Section 450.101, *Safety Criteria*.
- Section 450.108, *Flight Abort*.
- Section 450.110, *Physical Containment*.
- Section 450.111, *Wind Weighting*.
- Section 450.113, *Flight Safety Analysis Requirements-Scope*.

- Section 450.115, *Flight Safety Analysis Methods*.
- Section 450.133, *Flight Hazard Area Analysis*.
- Section 450.135, *Debris Risk Analysis*.
- Section 450.137 *Far-field Overpressure Blast Effects Analysis*.
- Section 450.139 *Toxic Hazards for Flight*.
- Section 450.161, *Control of Hazard Areas*.
- Section 450.169, *Launch and reentry collision avoidance analysis requirements*
- Section 450.213, *Pre-flight Reporting*.

3.3 **Related FAA Advisory Circulars**.

FAA Advisory Circulars are available through the FAA website, http://www.faa.gov.

- AC 413.5-1, *Pre-Application Consultation*, when published.
- AC 450.101-1A, *High Consequence Event Protection*, dated May 20, 2021.
- AC 450.108-1, *Flight Abort Rule Development*, dated July 27, 2021.
- AC 450.110-1, *Physical Containment Flight Safety Analysis*, when published.
- AC 450.115-1A, *High-Fidelity Flight Safety Analysis*, dated June 22, 2021.
- AC 450.115-2, *Medium-Fidelity Flight Safety Analysis*, when published.
- AC 450.119-1, *High-Fidelity Malfunction Trajectory Analysis*, when published.
- AC 450.123-1, *Population Exposure*, when published.

3.4 **Other References Related to Normal Trajectory Analysis.**

1. *Common Risk Criteria for National Ranges* (Rep. No. 321-10), White Sands, NM: Risk Committee, Range Safety Group, Range Commanders Council, 2010.
2. *Department of Defense World Geodetic System 1984, Its Definition and Relationships with Local Geodetic Systems*, Third ed., Amendment 1, Tech. No. NIMA TR8350.2, National Imagery and Mapping Agency, 2000.
3. Zipfel, P. H. *Modeling and Simulation of Aerospace Vehicle Dynamics* (Illustrated ed., Education). American Inst. of Aeronautics and Astronautics, 2001.
4. Vinh, N. X. *Flight Mechanics of High-Performance Aircraft* (Ser. 4). Cambridge: Cambridge University Press, 1995.
5. Regan, F. J. & Anandakrishnan, S. M., *Dynamics of Atmospheric Re-Entry* (AIAA Education). American Institute of Aeronautics and Astronautics. 1993.
6. Tewari, A. *Atmospheric and Space Flight Dynamics: Modeling and Simulation with MATLAB and Simulink*. Birkhäuser, 2007.

7. Gras, T., E. Larson, E. Porterfield, “Improved Correlation of Uncertainty Within Trajectory Sets,” *10th International Association for the Advancement of Space Safety Conference*, Los Angeles, California, May 2019.
8. *Global Positioning System Precise Positioning Service Performance Standard (GPS PPS PS).* DoD Positioning, Navigation, and Timing Executive Committee, 2007.
9. Leslie, F.W., and C.G. Justus, *The NASA Marshall Space Flight Center Earth Global Reference Atmospheric Model—2010 Version*, NASA/TM—2011-216467, https://ntrs.nasa.gov/citations/20110012696.
10. U. S. Standard Atmosphere, National Aeronautics and Space Administration, NASA-TM-X-74335, Washington D.C., October 1976, https://ntrs.nasa.gov/citations/19770009539.
11. Emmert, J.T., “Thermospheric mass density: A review,” *Advances in Space Research*, Volume 56, Issue 5, 2015, Pages 773-824, https://doi.org/10.1016/j.asr.2015.05.038.
12. Fink, R. *USAF Stability and Control DATCOM.* AFWAL-TR-83-3048. McDonnell Douglas Corporation, *Douglas Aircraft Division, for the Flight Controls Division, Air Force Flight Dynamics Laboratory*, Wright-Patterson AFB, Ohio. October 1960, revised November 1965, revised April 1978. See also http://www.pdas.com/datcomrefs.html for additional references.
13. Computational Fluid Dynamics Committee, *Guide for the Verification and Validation of Computational Fluid Dynamics Simulations*, AIAA G-077-1998(2002), 1 Jan 1998, https://doi.org/10.2514/4.472855.

The industry documents referenced in this paragraph refer to the current revisions or regulatory authorities’ accepted revisions.

4 DEFINITIONS.

For this AC, the terms and definitions from § 401.7, and this list, apply:

4.1 Debris Risk Analysis.

A quantitative evaluation of the probability and severity of potentially adverse consequences from hazards due to explosive and inert items from vehicle launch or reentry.

4.2 Degrees of Freedom (DOF).

The number of independent parameters that define a configuration or state for a mechanical system.

4.3 Flight Safety Analysis (FSA).

An FSA consists of a set of quantitative analyses used to determine flight commit criteria, flight abort rules, flight hazard areas, and other mitigation measures and to demonstrate compliance with the safety criteria in § 450.101.

4.4 State Vector.

A set comprised, at minimum, of the three-component position and three-component velocity associated with a point in time along a vehicle's trajectory. A state vector may also include vehicle mass, thrust, orientation, angular velocity, and other parameters.

5 ACRONYMS.

CFD – Computational fluid dynamics

DOF – Degrees of freedom

FSA – Flight Safety Analysis

GPS – Global Positioning System

HWIL – Hardware in the Loop

IIP – Instantaneous Impact Point

NASA – National Aeronautics and Space Administration

WGS – World Geodetic System

USAF – United States Air Force

6 PURPOSES OF NORMAL TRAJECTORY ANALYSIS.

6.1 **Background**.

In order to demonstrate compliance with § 450.101, an applicant must perform an FSA, unless agreed to by the Administrator based on demonstrated reliability, per § 450.113. An FSA consists of a set of quantitative analyses used to demonstrate compliance with the safety criteria, determine flight hazard areas and other mitigation measures, and determine flight commit criteria and flight abort rules. Sections 450.117 through 450.131 specify the requirements for analyses necessary to develop quantitative input data used to inform portions of the FSA. Section 450.117 specifies the constraints and objectives of analyses sufficient to characterize the trajectory of the vehicle during normal flight. Trajectory analysis is conducted by performing numerical simulations of the flight of a vehicle, incorporating all the vehicle properties (e.g. mass distribution, shape), external environment (e.g. atmosphere, wind), and all relevant physical forces (e.g. thrust, aerodynamics). A nominal trajectory is developed from a simulation where each input parameter is set to the expected value. Normal trajectories are developed by simulating flight where input parameters are instead sampled within the range of expected values. Thus, a trajectory analysis for normal flight is meant to analyze the variability in the intended trajectory and the uncertainties due to random sources of dispersion, such as winds and vehicle performance.

6.2 **Scope**.

6.2.1 For an FSA, the normal trajectory data must cover all phases of flight, as specified in § 450.113(a):

> (1) For orbital launch, from liftoff through orbital insertion, and through all component impacts or landings;
>
> (2) For suborbital launch, from liftoff through all component impacts or landings;
>
> (3) For disposal, from the initiation of the deorbit through final impacts; and
>
> (4) For reentry, from the initiation of the deorbit through all component impacts or landings.

6.2.2 There are two important clarifications regarding this scope:

- In accordance with §§ 450.113(a)(1) and (2), a flight safety analysis is performed and documented for an orbital or suborbital launch, respectively, from liftoff. Section 401.7 defines "liftoff" to mean any motion of the launch vehicle with intention to initiate flight. Therefore, the nominal trajectory for launch vehicle systems that employ a captive carry phase, such as a piloted or unpiloted aerial vehicle or balloon, begins at first motion of the launch vehicle with the intention to initiate flight.[1]
- For a single operation, there are normally a set of nominal trajectories, to include all parts of the vehicle. For each vehicle part, the normal trajectory analysis should continue until breakup is assured or impact occurs, as consistent with § 450.113(a).

6.3 **Use in Flight Safety Analysis**.

This AC provides acceptable means of compliance for the development of trajectory analyses that are required to address normal flight in accordance with § 450.117. Proper trajectory simulations are needed to support a valid FSA, which demonstrates compliance with acceptable risk thresholds and determines sufficient hazard areas. Flight planning also normally considers potential high-risk scenarios, and applies mitigations where possible, either implicitly (e.g. launching out over the ocean) or explicitly (e.g. avoiding overflight of islands before being sufficiently downrange). Normal trajectory simulations are necessary to perform the following general elements of a FSA:

- To verify that the vehicle flight plan is achievable under the conditions at the time of launch, in accordance with § 450.117(c).
- To identify the state vectors where a failure may occur, in order to initiate malfunction trajectory analysis, in accordance with § 450.119, or debris analysis, in accordance with § 450.121(c). The normal trajectory analysis is particularly

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[1] An FSA, including a trajectory analysis for normal flight, may not be required for the captive carry flight phase of flight, per § 450.113(b).

important for modeling the initial conditions for debris propagation of on-trajectory breakups and for simulation of flight in loss-of-thrust failures.

- To determine the region where population data will be required (together with understanding of the malfunction flight distribution), in accordance with § 450.123.
- To quantify the airspace volume and ground impact regions at risk due to planned launch vehicle ascent, reentry vehicle descent, jettison debris, and abort. These operations are required to develop land, waterborne vessel, and aircraft hazard areas in accordance with § 450.133.
- To establish adequate flight abort rules, including flight safety limits, that define when an operator must initiate flight abort, in accordance with § 450.108, if flight abort is used.

6.4 **Use for Other Parts of Licensing**.

Normal trajectories are also used in other parts of the license application. They are used as input to:

- Environmental review, per § 450.47.
- Safety-critical system design, test, and documentation, per § 450.143.
- Highly reliable flight safety system, per § 450.145.
- Collision avoidance analysis, per § 450.169.
- Pre-flight analysis, per § 450.213.
- Financial responsibility requirements, per Part 440.

6.5 **Analysis Applies to a Single Flight**.

A normal trajectory analysis should be performed for each planned operation of a vehicle separately and needs to consider potential variation within the operation (see paragraph 8.2). A license may apply to multiple flights, but the normal trajectory analysis is specific to each flight. The application requirements include submission of the products of a *representative* normal trajectory analysis, and the same process should be performed for all flights. Thus, the normal trajectory envelope does not encompass all potential flights of a vehicle that could occur, but the expected range of trajectories for a single flight. The normal trajectory analysis for each flight should be used to generate the pre-flight mission information, in accordance with § 450.213(b)(2).

6.6 **Flight Events**.

Normal trajectory analyses should define the times of the key planned events of flight. This includes:

- Motor ignitions and cutoffs;
- Guidance computer mode changes;
- Navigation data transitions;

- Configuration changes (separations, jettisons, and deployment of parachutes or aero-surfaces, etc.); and
- Instantaneous impact point (IIP) becoming defined (for reentry) or undefined (during ascent to orbit).

These events of flight are important to the overall FSA because they are associated with uniquely assigned failure probabilities and failure rates, debris lists, and flight safety system designs. For the nominal trajectory, times of key environmental conditions, such as maximum heating and dynamic pressure, should also be identified.

7 TRAJECTORY SIMULATION.

7.1 Consideration for Vehicle Systems.

Normal trajectory simulations typically require the system designer to integrate navigation and flight control subsystems to maintain controlled stable flight. Chemical propulsion rockets, which are long cylindrical bodies, tend to be aerodynamically unstable and develop aerodynamic structural loads that break the vehicle if the angle of attack exceeds a narrow margin. Launch and reentry systems that employ active guidance control should have some form of flight computer and sensor suite to measure linear and angular accelerations of the vehicle and compare current vehicle state with the nominal state, sense the error, and apply corrective flight controls. Flight controls include movable aerodynamic surfaces, propulsion thrust vector adjustment, or attitude control/throttle thrust system actions.

7.2 Simulation Implementation.

The software used for trajectory simulation should have acceptance within the industry or use verified methods of 6 degree of freedom (6DOF) simulation. A 6DOF simulation is a simplification of the real world. For example, it does not normally include detailed fluid dynamic calculations, but instead approximates aerodynamics and vehicle mass redistribution with a limited number of coefficients. The paragraphs below discuss the input parameters that are appropriate for a 6DOF simulation. Also, an important aspect of flight simulation is the numerical integration of the equations of motion. The algorithm for selecting the timestep should be evaluated to ensure that timesteps are sufficiently short so that vehicle behavior is accurately captured. This should be evaluated by testing the algorithm to ensure that resulting trajectories are stable with respect to small changes in the timestep approach. References 3, 4, 5, and 6 in paragraph 3.4 of this AC provide algorithms for 6DOF simulation for launch and reentry vehicles.

7.2.1 Small Vehicles.

For small, suborbital, solid rocket vehicles (e.g. less than 2,000 lbs. liftoff weight), a rigid body 6DOF simulation may be used, and a number of codes are available. Trajectory Analysis and Optimization Software (TAOS) from Sandia National Labs, Optimal Trajectories by Implicit Simulation (OTIS4) from NASA, and Program to Optimize Simulated Trajectories II (POST2) from NASA are examples. A more generalized toolset, such as Simulink with the Aerospace Blockset could also be used. These tools are also useful for large vehicles in initial planning phases, but the influence of non-rigid behavior should be incorporated for final flight planning.

7.2.2 Medium to Large Vehicles.

For most vehicles, a more sophisticated analysis is necessary to account for the vehicle-specific complexities in guidance, materials (bending), locations (reference frames and loads), and other factors. It is possible to create these simulations in multibody dynamics tools, such as Adams from MSC Software, or within MathWorks suite of tools (SimMechanics and Simscape Multibody). Other companies have analogous products (Siemens Motion, Ansys Motion, RecurDyn, etc.). Most operators develop their own toolsets and verify them against these codes to allow for more customization.

7.3 **Developing Vehicle Parameters**.

For a proper 6DOF analysis, there will be a significant effort to develop vehicle parameters and model the control system. The nominal values and the expected variation in them should be considered. Time, when used as a dependent variable in these parameters, does not refer to absolute mission time, but the time relative to significant flight events (this distinction is important when developing dispersed trajectories). Alternatively, some parameters like mass properties may be dependent on the propellant use and will scale differently depending on thrust control.

7.3.1 Mass Properties.

Mass properties data includes total mass, the components of moments of inertia, and the center of gravity location. These values should reflect changes in the vehicle configuration (e.g. jettison) and depletion of consumables (e.g. propellant burn or venting). The mass properties should be developed for each vehicle configuration as a function of propellant load. For reentry vehicles, these values sometimes do not change after completion of the deorbit burn. Large control surface deflections and vehicle bending should be considered. Movement of propellant within the fuel tank should be accounted for where relevant. Propellant moves due to inertial forces and depends on vehicle orientation. Different vehicles have a variety of ways of compensating for propellant motion; these will affect the mass distribution. The mass properties will typically be developed in concert with the propulsion and any changes required in vehicle configuration. Uncertainties in propellant load and payload mass should be considered.

7.3.2 Aerodynamic Properties.

The complexity of aerodynamic parameters depends on the control system of the vehicle. For a nearly axisymmetric thrusting rocket, simple coefficients of force will suffice: a set of lift and drag or component force coefficients versus Mach, altitude, and angle of attack, and the center of pressure versus free stream condition. A vehicle with controlled lift, asymmetry, and/or under aero-surface control typically requires more complex aerodynamic coefficient data. The coefficients may need to be dependent on the flight speed, temperature, pressure, viscosity, angle of attack, lateral g-load, control surface deflection, or any number of other values. Control surfaces should be modeled.

To develop aerodynamic properties for a 6DOF simulation, a computational fluid dynamics model, wind tunnel, drop test, and/or other empirical data should be used. The United States Air Force Stability and Control Datcom (reference 12 of paragraph 3.4 of this AC) provides a review of approaches. The model should consider the entire flight regime from rarified atmosphere hypersonic to sea level subsonic. Gaps in the model can lead to significant over or underestimation of vehicle performance.

7.3.3 Propulsive Properties.

For a 6DOF simulation, the propulsive properties include the thrust magnitude, thrust vector angle, and moment arm of the thrust. To determine the propulsive capability of the vehicle, combustion modeling, static thrust tests, and/or flight data should be used. These should have measures and estimates for the maximum external operating pressure (e.g. sea level) and for vacuum performance and efficiency. The values (throttle level, thrust vector) for a particular operation are usually developed as part of an optimization process to achieve the objectives and avoid violating vehicle flight constraints. The values determined in the optimization are then the data input to the guidance. Alternatively, initial conditions and guidance rules could be developed through an optimization, and then feedback in the guidance program could set the values as the flight (or simulated flight) progresses. The simulation may also take into account the effects of pitch damping and/or jet damping.

7.3.4 Guidance, Navigation, and Control Systems.

The guidance, navigation, and control systems should be modeled in the 6DOF simulation. These may be implemented as software simulations or using “hardware-in-the-loop” (HWIL) that interfaces with the trajectory simulation software. The same guidance program should be used as in the flight hardware, although, if not using HWIL, a different implementation may be used. When a pilot is in control of the vehicle, then the simulation should be derived from the output of a flight simulator. Control systems may be simulated through parameters such as gain and damping, limits on the commands like maximum deflection and rate, latency, and limits on the vehicles structure and performance. For modeling sensors, factors like latency, persistence, filtering, and variance should be considered.

7.3.5 Earth Model.

An accurate model of the Earth’s gravity field is required: World Geodetic System 1984 (WGS 84) (reference 2 of paragraph 3.4 of this AC) or equivalent. For reentry vehicles, terms up to and including the 4th order zonal harmonic (J4) should be included. For launch, terms up to J2 should be used. Additional terms may also be included.

7.3.6 Configuration Management.

A system for tracking and controlling versions of software, vehicle data, and flight-specific input data should be maintained. In many situations, analysts may use different versions of software through the development process of a vehicle, but the correct validated version should be used for flight. Also, updated vehicle data based on test results, flight information, etc. may be available. Further, many potential flight profiles may be developed. A rigorous configuration control system should be maintained to ensure that the normal trajectory analysis corresponds to the actual flight plan loaded on the vehicle at initiation of the operation.

7.4 **Output Interval**.

Normal trajectory state data should be output for use in subsequent analyses at short time intervals (but not as short as the integration time intervals). The intervals should be short enough that the ground debris impact regions overlap enough to provide smooth impact probability contours for failures with the smallest dispersions, just as required for malfunction trajectories (§ 450.119(b)). The smallest dispersions should consider only uncertainty, not variability, as described in paragraph 8.2 of this AC, and are usually due to loss-of-thrust and on-trajectory breakup events. The interval must be 1 second or less, in accordance with § 450.117(d)(4); normally, 10Hz or greater frequency is used for nominal trajectories.

8 NORMAL TRAJECTORY TYPES

8.1 **Nominal vs. Normal**.

Section 450.117(a) states that the normal trajectory analysis must include the nominal trajectory and two sets of trajectories to account for uncertainty and variability. A nominal trajectory is a single simulated trajectory of the launch or reentry vehicle where all vehicle aerodynamic parameters are as expected, all vehicle internal and external systems perform exactly as planned, and there are no external perturbing influences other than the nominal atmospheric drag and gravity. A set of normal trajectories include the effects of statistical perturbations on vehicle performance and aerodynamic parameters sampled across uncertainty ranges assigned to each flight performance or environmental parameter. The normal trajectory set is often referred to as the set of “dispersed” trajectories. The nominal trajectory can be thought of as the “planned” normal trajectory with all perturbations set to zero.

8.2 **Variability vs. Uncertainty**.

The distinction between the two sets of trajectories is based on what can and cannot be known at the time of mission initiation (aleatory and epistemic uncertainty, respectively). For example, a launch window is often many minutes or hours, but the time of launch within the window is known very precisely before launch commit occurs. Thus, the *uncertainty* in launch time is small (microseconds) but the *variability* is the length of the window.

8.3 **Significant Influence**.

The rule does not intend for applicants to characterize the influence of all random uncertainties or variability, but only those with a significant influence on the potential impact locations for hazardous debris. The FAA considers “a significant influence” to include any parametric uncertainties that affect the crossrange IIP location or downrange IIP rate by at least one percent relative to the combined uncertainty of all parameters. IIP location and rate are used because they represent a convenient surrogate for the potential impact locations of hazardous debris. The applicant may consider additional parameters as well to provide more mission assurance.

8.3.1 Procedure.

1. To determine which parameters are significant, first, a baseline for trajectory uncertainty should be established. This is accomplished by:
    a. Identifying several parameters for which the uncertainty is likely to be most significant (e.g. thrust magnitude and direction uncertainty);
    b. Computing dispersed trajectories accounting for those uncertainties together; and
    c. Measuring the statistics (mean, standard deviation) of both the cross-range IIP and the downrange IIP rate.
2. Then other potential sources of uncertainty should be examined. This is accomplished by:
    a. Computing additional sets of dispersed trajectories with both the baseline uncertainties and with the additional uncertainties (usually logically connected subsets, e.g. lift coefficients)
    b. Measuring the statistics of both the cross-range IIP and the downrange IIP rate. The mean of the baseline should be used, not the revised mean, when computing statistics.
    c. Comparing the statistics of the two metrics to the baseline case, and if the statistics do not change by more than 1 percent, then these uncertainties in the subset need not be considered. They should be compared at the 95 percent or greater confidence level at a minimum (e.g. two sigma for a normal distribution).
3. A design of experiments approach may be used instead to evaluate which parameters are significant, still using these two metrics to evaluate significance.

8.4 **Normal Trajectory Set Due to Variability**.

A set of trajectory simulations based on known variations must be used to define a data set of the range of possible flights that could occur for an operation, in accordance with § 450.117(a)(1). A flight safety analysis should demonstrate that each trajectory in this set, when treated as the planned flight, meets the risk criteria in § 450.101 because a decision not to fly one of these trajectories could be made prior to flight. In effect, each variable trajectory is treated like a nominal trajectory. These variabilities are in the context of a single planned operation. If an analysis is considering multiple operations, the variability across operations should also be considered.

8.4.1 Wind Variability.

A contributor to normal trajectory variations is the range of wind conditions that the vehicle will experience. For a controlled vehicle, guidance system logic will normally adjust the flight path of the vehicle to meet certain conditions. These conditions could be vehicle constraints, such as limiting the aerodynamic loads on the vehicle or targeting a particular orbit or downrange impact point. For uncontrolled vehicles, wind is a key element of the trajectory determination. Atmospheric data are discussed in Chapter 9 of this AC. Examination of wind conditions is also normally part of the analysis to establish mission rules, as under some conditions, a vehicle will not be able to meet mission objectives and/or meet safety criteria.

8.4.2 Operation Window Variability.

For some missions, the trajectory that is flown may change significantly during the operation window. This occurs on launch when targeting a particular orbital position, but the launch vehicle is moving due to Earth rotation. Likewise, as cryogens boil off, the vehicle mass changes. These differences are variability, but the differences in flight due to engine performance, meteorological perturbations, etc. are uncertainties. For reentry, an operation may initiate from different orbits or on an ascending or descending node, resulting in very different trajectories.

8.4.3 Platform Variability.

When a mobile platform is used, such as a ship or an aircraft, the location of a launch or landing may have significant variability. Note that an operation should not be allowed if the platform will not be within the range of pre-examined scenarios.

8.4.4 Discretization of Variability.

Development of trajectories to describe variations of flight should be sufficient to envelope the parameter variation and resulting trajectories. Since many variations are continuous, it is impossible to evaluate every possible trajectory within the range of variability. The edges of the ranges should be analyzed, at a minimum. Additional intermediate trajectories may also be necessary to resolve relevant differences in risk. For example, if the trajectory changes during the launch window, then at least the beginning and end of the window should be examined, and if a significant population center would be directly overflown by an intermediate trajectory, that one should be analyzed as well.

8.5 **Normal Trajectory Dispersion Due to Uncertainties**.

In accordance with § 450.117(a)(2), an applicant must develop a set of trajectories that characterize uncertainty. These contribute to the uncertainty in debris impact dispersions and planned jettison body impact containment areas. Although there is a particular expected trajectory, or set of trajectories, given launch conditions and nominal data values, it is recognized that this trajectory is a deterministic prediction of a launch or reentry profile that has inherent uncertainties that need to be evaluated in a statistical sense. The launch or reentry system itself has physical parameters that are not exactly known. The best estimates of uncertainty should be used, not exaggerating or over-stating in an attempt to be “conservative.” For safety purposes, variability should be used to consider conservatism, but larger dispersions (more spread-out risk) is not conservative for exposed people or assets close to the nominal flight path, such as ships and aircraft. If a wider range is necessary, a specified larger sigma level should be used to define the nominal envelope, such as 6 or 9 sigma, instead of 3 sigma.

8.5.1 Sources of Uncertainty.

The license applicant is required to evaluate the sources of uncertainty that will result in flight variations that have a significant influence on the expected trajectory. If the effect of the uncertainty in a parameter on the flight simulation is shown to be negligible compared to other included uncertainties, it may be ignored. It is not uncommon for a few large uncertainties to dominate the solution and simplifying assumptions can be made. These assumptions and justifications should be documented.

8.5.1.1 Motor Performance**.**

Motor performance is likely the largest driver of uncertainty, as it fluctuates in both magnitude and thrust misalignment. There should be empirical data from static thrust testing to calibrate this uncertainty. Subsequent flights may be used to refine this uncertainty.

8.5.1.2 Aerodynamic Parameters**.**

Uncertainty in drag and lift coefficients should be developed along with the nominal parameters using computational fluid dynamic models, wind tunnel data, and/or flight data. Normally for rocket powered flight, the uncertainties in aerodynamic parameters are negligible compared to other uncertainties, but they may be significant during flight controlled by aerosurfaces or during periods of significant weather deviations (layers of hot or cold atmosphere, wind shear, etc.).

8.5.1.3 Mass properties**.**

The uncertainty in mass will affect the center of gravity and the moment coefficients alike. This will most likely be due to uncertainty in the propellant mass and density as it is loaded pre-mission. There should be an acceptable range for ground operations to load propellant that can be used to develop the uncertainty. The uncertainty in the structural and payload masses are normally smaller in magnitude.

8.5.1.4 Control System.

Uncertainty in the control system can come from many sources. The uncertainties in thrust gimbaling, aero-control surfaces, tank pressures of thrusters, or pressure in hydraulics should be considered. This should consider potential oscillations and harmonics in the control system loops, and uncertainties in the response time. The uncertainty should be derived from empirical data static thrust testing, drop tests, and other forms of component level and flight testing and/or from numerical modeling.

8.5.1.5 Navigation.

The navigation system will have uncertainty, such as, due to tolerance in the inertial measurements, drift, noise, or dilution of precision of Global Positioning System (GPS). Depending on the sensor fusion the uncertainty may need to be mitigated or amplified. Data on a sensor performance should be available from manufacturer specifications and/or performance standards, such as reference 8 of paragraph 3.4 of this AC for GPS.

8.5.1.6 Environment.

There exists uncertainty in the environment, including wind, atmospheric density, and temperature. These may not have a significant influence on flight, especially if wind is handled as a variability. This is discussed further in chapter 9 of this AC.

8.5.2 Applied Probability and Number of Trajectories.

Dispersed trajectory simulation for random uncertainties requires each parameter to be defined with a mean value and an estimated probability density function to allow random sampling of the parameter. Typical uncertainty distributions are Gaussian, uniform and log-normal, but other distributions may apply, especially if performance test data is available to support development of alternative distributions. The number of dispersed normal trajectories required to characterize the statistical attributes of the normal trajectory range of uncertainty depends on the number of contributing factors and the weighting of the factors. Typically, 500 to 1,000 dispersed trajectories are considered adequate. If there are significant correlations among the uncertainty parameters, the applicant should apply correlated random sampling to capture those relationships. Each sample may be considered equally likely, or the applicant may assign a relative probability to each sample, if supporting data can be provided to establish such weighting.

8.5.3 Multiple Uncertainty Sets for Different Flight Profiles.

The need for multiple uncertainty sets depends on the difference between the trajectories developed in the variability analysis. For some cases, such as re-entering from an ascending or descending node, a different uncertainty set is clearly required. However, for smaller differences between variability trajectories, separate uncertainty sets would not be meaningful. When separate uncertainty sets are not used, they should be translated to each trajectory in the variability set for analysis. Justification for the use or non-use of different uncertainty sets should be documented.

8.5.4 Normalizing Event Times on Normal Uncertainty Trajectories.

The applicant should normalize the event times of the set of dispersed normal trajectories with the planned nominal trajectory time range to assure that covariance data can be properly generated for each normal trajectory time step. It may be possible to normalize controlled reentry trajectories based on trajectory attributes such as deorbit burn phases or reentry flight path angles for the purpose of developing state vector covariance. Such event-based time scaling allows for correlating the time of state vectors in dispersed trajectories to the normal trajectory time based on events. Each dispersed trajectory will typically have events at different flight times than the normal. However, the state of the vehicle is more important than the flight time for many aspects of risk analysis. Thus, for use in analysis, each state vector in a set of normal trajectories should be assigned a "nominal-equivalent time." The calculation of nominal equivalent time is discussed in reference 7 of paragraph 3.4 of this document.

8.5.5 Statistical Representation of Normal Uncertainty Trajectories.

Statistical analysis can be performed on the dispersed trajectory set to develop a 6 x 6 covariance matrix at each trajectory time step (typically 1-second intervals). This state vector covariance matrix provides the variances of the position and velocity of the vehicle (diagonal terms) and the correlations among the position and velocity terms. The covariance matrix should be computed by taking statistics as computed from the statistics of state vectors as a function of nominal-equivalent time.[2]

9 ATMOSPHERIC EFFECTS

A trajectory analysis must account for atmospheric conditions that have an effect on the trajectory, including atmospheric profiles that are no less severe than the worst conditions under which flight might be attempted, and for uncertainty in the atmospheric conditions, in accordance with § 450.117(c). The nominal trajectory, the variability trajectory set (including worst conditions), and the uncertainty trajectory set(s) should use different sets of atmospheric data, as discussed below. The normal trajectory analysis should be performed well ahead of the mission using historical data and statistical models, then the planned trajectory re-simulated with the latest atmospheric forecast during the operation countdown to ensure it is within the bounds of the trajectories previously analyzed. The most important atmospheric parameters are air density and wind; pressure and temperature are secondary. The data is a function of altitude, geographic location, and time.

9.1 Data Sources.

9.1.1 Global Data.

The primary data source is the Earth Global Reference Atmospheric Model (Earth-GRAM), in reference 9 of paragraph 3.4 of this AC, which includes Range Reference Atmosphere data. This is a design reference atmosphere that provides complete global geographical variability, complete altitude coverage (surface to orbital altitudes), and complete seasonal and monthly variability of the thermodynamic variables and wind components. The Earth-GRAM software includes the capability to produce Monte Carlo data profiles.

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[2] Determining statistics as a function of flight time, without event-based scaling, may not be a good fit to the state vector distribution, especially during overflight and for landings. This can lead to excessively large impact distributions. Event-based timing reduces time range uncertainty that allows improved accuracy of failure probability and debris list applications that have time varying attributes.

9.1.2 Historical Data.

Historical and local data should be used to evaluate trajectory variability, including worst conditions. There are two data sources:

- Databases maintained by the launch or reentry site, and
- National Oceanic and Atmospheric Administration (NOAA) Radiosonde database (https://ruc.noaa.gov/raobs).

This data should be used within a limited distance from the location and day of the year from which they were measured. Only data profiles that extend above the jet stream (e.g. at least 50,000 feet in elevation) should be used; others should be excluded. Local data should be used within 50 to 100 miles of the measurement point up to the maximum altitude where it is valid. If there is insufficient historical data (e.g. for oceanic sites), then Earth-GRAM Monte Carlo profiles should be used for the entire altitude range. Typical atmospheric and “wind aloft” data is discretized at resolutions on the order of ~500-1,000 feet above ground level.

9.1.3 Forecast Data.

For development of trajectories in the launch countdown, atmospheric forecasts are preferred. These forecasts have been found to have high accuracy for predictions 24-48 hours in advance, unless there is a significant weather feature in the region of the site in the period of interest (e.g. a front moving through). For near-vertical flight, a one-dimensional profile from the forecast is sufficient. Forecasts include the North American Mesoscale Model and the Global Forecast System.

9.1.4 Combining Data.

Since data from different sources should be used, it needs to be combined together. However, a discontinuity in atmospheric data leads to errors in simulations, so the data should be combined smoothly, by fairing the data. The fairing region should be the outer 25 to 50 percent laterally of the local data and the upper 10 to 20 percent in altitude (always starting above 45,000 ft.).

9.1.5 Air Density.

For trajectory analysis, the vertical profile of density is most important. In the troposphere and below, the temporal and spatial variation of density are relatively small. High-altitude (above 100 kilometer (km)) density is very important when the vehicle is re-entering, especially for very small reentry angles (e.g., less than a few degrees from horizontal). For reentry, the density of the exosphere can vary significantly as a function of time due to space weather. Reference 11 of paragraph 3.4 of this AC contains a review of modeling this effect.

9.1.6 Wind.

The importance of wind variability on the trajectory is much higher in the vicinity of the launch or landing location, and the effects are much smaller when the vehicle is above the jet stream. Surface winds are often particularly important for two reasons: the vehicle is moving relatively slowly, so effects can be strong, and the vehicle may need to avoid obstacles near the site (e.g. towers). Wind velocity at higher altitudes may prevent the vehicle from achieving its intended trajectory, and it should be assured the vehicle has sufficient control authority and does not exceed structural limits. These effects are dependent both on the wind velocity and the gradient (wind shear). The nominal trajectory, however, must be generated without wind, in accordance with the definition of "nominal" found in § 401.7, which excludes external perturbing influences other than atmospheric drag and gravity.

9.2 **Worst Case Analysis**.

Normal flight behavior should be closely evaluated by mission planners to optimize the mission trajectory and to verify that the vehicle can perform the mission over a wide range of environmental conditions (i.e. the range of winds at the launch/reentry site). This reduces the likelihood of a failure due to aerodynamic effects. The variability study should reveal what the reasonable limits are for worst case atmospheric conditions beyond which a launch or reentry attempt would not be made.

9.2.1 Data analysis.

Trajectory simulation should be performed for a large range of atmospheric profiles. For density, the Earth-GRAM mean density may be used as a function of location for all ascent analyses, and below 100 km for re-entries. Likewise, for wind, above the historical profiles, the Earth-GRAM annual mean wind may be used. However, the variation in density above 100 km and in wind below 50,000 feet should be evaluated for worst case conditions. The ability of the vehicle to achieve mission objectives with sufficient confidence should be evaluated for each simulation. If any profiles are not acceptable, then the criteria for acceptable conditions should be adjusted to preclude those. This analysis should be examined separately for each variation of the operation. In addition, the most extreme resulting acceptable trajectories, in terms of lateral range of present position and IIP, should be identified.

9.2.2 Limits.

Wind is normally the only atmospheric variation relevant to limits based on trajectory design. Variations in temperature or density are typically too small to affect the trajectory. However, if the vehicle performance is sensitive to these variations within the potential range of values, criteria may need to be established. Mission rules should be established regarding flight acceptability based on the following criteria:

- Wind speed at the surface (or drop location for air-launched rockets) which may be a function of wind direction;
- Wind speed (or integrated wind effect) as a function of altitude and optionally direction; and
- Wind shear as a function of altitude.

Note: For reentry, the trajectory should be simulated with the best available upper atmosphere density data and deorbit burn adjusted accordingly.

10 SATISFYING APPLICATION REQUIREMENTS.

The license applicant must provide sufficient data and explanation of assumptions and methodologies, to allow the FAA application review team to evaluate the validity and completeness of trajectory analyses.

10.1 Methodology Description.

In accordance with § 450.117(d)(1), the applicant must submit a description of the methods used to characterize the vehicle’s flight behavior throughout normal flight. This must be done in accordance with § 450.115(c), which requires a description of:

(1) The scientific principles and statistical methods used;

(2) All assumptions and their justifications;

(3) The rationale for the level of fidelity;

(4) The evidence for validation and verification required by § 450.101(g);

(5) The extent to which the benchmark conditions are comparable to the foreseeable conditions of the intended operations; and

(6) The extent to which risk mitigations were accounted for in the analyses.

10.1.1 Provisions.

For normal trajectory analysis, this description should encompass software, input data, and the process. Normal trajectory analysis is a critical element of a successful mission and all FSA is dependent on a high-fidelity simulation of how the vehicle is expected to operate under normal conditions. A well-documented and understood methodology is thus, a critical element of rocket operation, important both to the operator and to safety regulators. Literature references to standard approaches, along with a description of how the applicant uses them, are very useful.

10.1.2 Software.

An applicant may use an existing simulation software program, develop a new one, or use a hybrid approach. For all such software, the applicant should provide a detailed technical description of the software, including equations and the approaches used for numerical evaluation. The applicant should provide evidence of software validation through comparison with existing industry-standard software and/or against flight experience. The applicant should specifically describe any customization of pre-existing software. The approach to implementing the guidance program, simulating sensors, and simulating control systems should be described, including equations, assumptions, and justification. Evidence should be provided demonstrating the accuracy of these approaches, and justification for the fidelity provided. The applicant is not required to provide the simulation software itself, but it may be beneficial to provide understanding and clarity and to streamline application evaluation.

10.1.3 Data.

The applicant should provide a description of the methods used to develop input data for the simulations. The data includes control logic, vehicle data, and environmental data. Control logic includes scripts, configuration files, etc. that are input to the simulation program, as well as inputs to the guidance program. Vehicle data is the most significant portion of the input, and may be obtained by simulation, measurement, and/or experiment. The description of the development of the input data depends on the approach used.

10.1.3.1 Numerical Simulation**.**

When numerical simulation is used to generate the data, the key principle is demonstrating that the numerical approach matches the real-world with sufficient fidelity. The applicant should also describe the process for evaluating the uncertainty in the results and the different configurations of the vehicle that are evaluated.

10.1.3.1.1 Example.

For example, to develop aerodynamic data, normally a computational fluid dynamics (CFD) code is used, together with Datcom (reference 12 of paragraph 3.4 of this AC). A key input is the vehicle surface geometry. The applicant should describe the process to ensure the surface geometry matches the actual vehicle and why the level of fidelity of the numerical representation is sufficient to adequately measure the aerodynamic properties. Any changes to the vehicle surface during flight affect the properties; the applicant should describe these states, and when there is a continuous change (e.g. a moving surface), how the continuously changing properties are evaluated and implemented. Also, the applicant should specify the CFD code used, the rationale for why it was selected, the validation and verification process (see reference 13 in paragraph 3.4 of this AC), and specifically explain any custom implementations.

10.1.3.2 Experimental approach**.**

When experimental approaches are used, the experimental design is essential for achieving accurate results. The applicant should provide an overview of the test object hardware and how it relates to the vehicle, the measurement methods, and the approach to determine the various experimental conditions. The description of the approach should include the range over which the experimental results are valid and the method for determining uncertainties.

10.1.3.3 Measurement**.**

Some vehicle data can be directly measured or obtained from component specifications. The applicant should describe the measurement process for each data element and the uncertainty associated with the measurement method. Often measurements are aggregated for input to the simulation; the applicant should describe the process to ensure that measurements are complete and aggregation accurately reflects the physical vehicle. For example, if masses of components are used to determine mass properties, the operator should describe the process to ensure that all components are incorporated in the calculation and how they are accurately reflected.

10.1.4 Process.

The planned flight path must be submitted for each mission, in accordance with § 450.213(b)(2), and the analysis differs for each one. First, the target of each flight is usually different. Second, the vehicle configuration is often different (e.g. different payload). Third, the lessons learned from vehicle development and actual flight data are incorporated into future simulations. Clarity in these processes are critical for mission success and safety.

10.1.4.1 Ongoing Improvement**.**

The applicant should describe the process for incorporating additional information into the simulation approach during the development process.

10.1.4.2 Configuration Control**.**

The applicant should describe the configuration control process to ensure that the correct versions of the simulation tool and data are used and that it matches the actual vehicle configuration for flight. This can be a point of confusion, there are often many potential flights examined, such as those for the variability study.

10.1.4.3 Variability**.**

The applicant should describe the approach for identifying the variability of a potential mission and how the specific trajectories are selected to characterize and analyze the variability, following the discussion in paragraph 8.4 of this document.

10.2 **Input Data for Trajectory Analysis**.

In accordance with § 450.117(d)(2), the applicant must provide all the input data including uncertainties that were used to define the launch or reentry vehicle flight characteristics. These data include all the parameters that describe the mass, aerodynamic, and propulsive properties, the data input to the guidance program, and the atmospheric conditions used.

10.2.1 Nominal Data Set.

The input data should be provided as the files that are input to the simulation program, along with a document defining each data element, including the physical meaning, units, and coordinate system (as appropriate). This data should be provided for a representative nominal trajectory. Normally, this includes sets of tabular data representing the data elements as a function of independent parameters (e.g. propellant remaining, angle of attack, etc.), with different tables for each different vehicle configuration during the flight. This dataset should be sufficient for an independent run of the same simulation program that the applicant uses.

10.2.2 Uncertainties.

The applicant should provide the quantitative uncertainties that are used to develop the normal trajectory dispersions. For each parameter that has a relevant uncertainty, the applicant should provide the functional form of the uncertainty distribution and the numerical parameters that define the distribution. For example, if a parameter has normal uncertainty, the applicant should provide the mean and the standard deviation (the mean should have been used to generate the nominal). If there are correlations between uncertainties in parameters, the applicant should provide data describing these, such as a correlation matrix. The data should be sufficiently annotated that the approach to drawing random sets of the parameters is apparent.

10.3 Worst Atmospheric Conditions.

In accordance with § 450.117(d)(3), the applicant must submit the worst atmospheric conditions under which flight might be attempted, and a description of how the operator will evaluate the atmospheric conditions and uncertainty in the atmospheric conditions prior to initiating the operation. The worst atmospheric conditions should describe the constraints on winds, temperature, or other atmospheric parameters that preclude flight of the vehicle. These typically include constraints on surface level winds, wind shears, or high-altitude winds. The limits may be derived from vehicle structural limits or from limits of the ability of the vehicle to navigate. It may be that the worst conditions vary depending on the mission profile. The applicant may either provide the worst case conditions acceptable for flight under any conditions, or the worst case conditions associated with the representative flight provided below. In either case, the applicant should also describe the process for determining these constraints and how the atmospheric conditions are evaluated during the launch countdown to assess whether the flight may proceed.

10.4 Trajectory Outputs.

The applicant must provide trajectory data developed for a representative trajectory analysis, in accordance with § 450.117(d)(4). A representative trajectory analysis is an analysis that defines a flight to meet the objectives of a specific anticipated mission (e.g. placing a payload in a particular transfer orbit from a particular launch site). Thus, this should be the same analysis that would be performed in anticipation of that mission. The applicant should describe the mission objectives and vehicle constraints that are assumed for the representative trajectory analysis. If a flight includes parallel flight segments, nominal trajectory data and both types of normal trajectory sets should be provided for all segments.

10.4.1 Data Specification.

All trajectories submitted with the application must include position, velocity, and orientation, at a maximum of 1 second intervals (1 Hz or greater frequency), in accordance with § 450.117(d)(4). These data are commonly called state vectors, and include the “from operation reference time,” and the three components for each position, velocity, and orientation. Additional data elements for each state vector, such as angular velocity, thrust, vehicle mass, and vacuum IIP location, may also be provided and are encouraged. The timing of key flight events (ignitions, engine shutdown, configuration changes, etc.) in each trajectory should also be provided. No particular file format is recommended, but all trajectory submissions related to an application should be in the same format, and follow the guidance below.

10.4.1.1 Coordinate System Definition**.**

The applicant should provide a mathematical description of the coordinate system, including units, in which the data is provided. Normally position and velocity are provided in Cartesian coordinates, with coordinate system origin at the center of the Earth or at the launch pad. Orientation of the vehicle is specified as a rotation from the coordinate frame to the vehicle axes, either as Euler angles or a rotation matrix. The coordinate system may either be in an inertial frame or rotate with the Earth. The applicant should specify each of these, including any conventions (left- or right-handed, Euler angle sequence, etc.).

10.4.1.2 File Formats**.**

The trajectory data should be submitted in a machine-readable format, such as an ASCII text file or a standard spreadsheet file format. For the trajectories, the data should be in tabular form where each record represents a different time of flight and the fields are the elements of the state vector. Extraneous information that would hinder machine processing is discouraged. Event names and times may be included in additional fields of the trajectory files or in separate files. When providing a set of trajectories, it is preferable to provide each trajectory in a separate file, along with an index file describing the purpose of each trajectory.

10.4.2 Nominal Trajectory.

The nominal trajectory required in accordance with § 450.117(d)(4)(i) is the product of the 6DOF analysis with all input data set to the nominal value, per paragraph 8.1 of this AC. In order to ensure consistent interpretation and clear understanding, the applicant should also provide graphics of the nominal trajectory, including:

- Present position and the IIP plotted on a map, with times of key events noted;
- Range vs. altitude;
- Velocity magnitude and geodetic flight path angle vs. time; and
- Geodetic pitch, yaw, and roll vs. time.

10.4.3 Trajectory Set Characterizing Variability**.**

The applicant must provide a set of trajectories that characterize variability in the intended trajectory based on conditions known prior to initiation of flight, in accordance with § 450.117(d)(4)(ii). The trajectory data should be the result of the analysis described in paragraph 8.4 of this AC for the same representative mission as used for the nominal trajectory. The trajectories should be clearly labeled to indicate the variability parameters. The applicant should also provide graphical depiction of the trajectories, at a minimum to include present position and IIP on a map, along with times of key events.

10.4.4 Trajectory Set Characterizing Uncertainty.

The applicant must provide a set of trajectories that characterize how the actual trajectory could differ from the intended trajectory due to random uncertainties, in accordance with § 450.117(d)(4)(iii). The trajectory data should be the result of the analysis described in paragraph 8.5 of this AC for the same representative mission as used for the nominal trajectory. These trajectories are typically random samples and are simply indexed by number, but if another scheme is used, the applicant should describe the sampling approach and specify the probability of each trajectory. The applicant may instead submit a covariance matrix (see paragraph 8.5.5 of this AC) provided that the trajectory uncertainty follows a normal distribution. When developing the covariance, times of the random trajectories should be scaled based on event times (see paragraph 8.5.4 of this AC).

OMB Control Number: 2120-0746
(Expiration Date: 08/31/2023)

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Subject: (insert AC title/number here)   Date: Click here to enter text.

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