AST Commercial Space Transportation
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Workshop on Advisory Circular (AC) §450.117-1

Trajectory Analysis for Normal Flight

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Background on Advisory Circulars

Advisory Circulars (ACs) are being used to supplement streamlined regulations by the Federal Aviation Administration (FAA), Commercial Space Transportation (AST).

The goals of the ACs are to:

- Further explain the meaning of the regulatory text and its intent
- Provide **a** means of compliance

The ACs are guidance, not a regulation, and so compliance is voluntary.

To demonstrate compliance using an AC, the entire AC must be implemented. This means that the FAA must approve any variance from a “should” statement in the AC.

DISCUSSION IS ENCOURAGED

We have up to two hours today, with incremental periods for Q&A as we step through the chapters of the AC

NOTE:

Answers by presenters are preliminary; a future revision of the AC is the official response

AC 450.117-1 Overview

AC organization

- Chapter 1
  - Explains the purpose of the AC, analysis scope, description of methods, and level of imperatives
- Chapter 2
  - Describes applicability of the AC
- Chapter 3
  - Covers applicable regulations and guidance documents
- Chapter 4 & 5
  - Cover terms and definitions and explain acronyms present in the AC

AC 450.117-1 Overview

AC organization

- Chapter 6
  - Explains the purposes of Normal Trajectory Analysis within Flight Safety Analysis, and covers use within other parts of licensing
- Chapter 7
  - Gives guidance for Trajectory Simulation and considerations for vehicle parameters and modeling
- Chapter 8
  - Distinguishes nominal from normal, addresses development of trajectories to capture variability and uncertainty, and describes significant influence
- Chapter 9
  - Addresses atmospheric effects, data sources and worst-case analysis
- Chapter 10
  - Addresses satisfying application requirements, describes methodology, input data for trajectory analysis, worst case atmospheric conditions, and trajectory outputs

Chapter 4 – Definitions

There are four definitions:

- **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.
- **Degrees of Freedom (DOF) –**
  - The number of independent parameters that define a configuration or state for a mechanical system.

ACs only define terms not defined in the regulation (§401.7).

- **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.
- **State Vector –** (standard definition)
  - 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.

Chapter 4 – Definitions

Discussion

Floor open for questions/comments
Either verbally or via comments

Chapter 6 - Purposes of Normal Trajectory Analysis

Section 6.1 - Background:

- 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 :
    - vehicle properties (e.g. mass distribution, shape)
    - external environment (e.g. atmosphere, wind)
    - relevant physical forces (e.g. thrust, aerodynamics)

Section 6.1 - Background

- A **nominal trajectory** is developed from a simulation where each input parameter is set to the expected value
    - *Winds are neglected
- **Normal trajectories** are developed by simulating flight where input parameters are instead sampled within the range of expected values

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

Section 6.2 - Scope

There are two important clarifications regarding this scope:

1. A flight safety analysis is performed and documented for an orbital or suborbital launch from liftoff
   - Liftoff defined as any motion of the launch vehicle with intention to initiate flight
   - For launch vehicle systems that employ a captive carry phase, begins at first motion of the launch vehicle with the intention to initiate flight [1]
2. 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

[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).

Section 6.3 - Use in Flight Safety Analysis

Proper trajectory simulations → Valid FSA → Compliance with acceptable risk thresholds and sufficient hazard areas

- Flight planning 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 an FSA:

Verify that the vehicle flight plan is achievable under the conditions at the time of launch

Identify the state vectors where a failure may occur, in order to initiate malfunction trajectory analysis

Determine the region where population data will be required (together with understanding of the malfunction flight distribution)

Quantify the airspace volume and ground impact regions at risk due to planned launch vehicle ascent, reentry vehicle descent, jettison debris, and abort

Establish adequate flight abort rules, including flight safety limits, that define when an operator must initiate flight abort, per § 450.108, if flight abort is used

Normal trajectory analysis is particularly important for:

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

Section 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

Section 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
  - A license may apply to multiple flights, but the normal trajectory analysis is specific to each flight

Section 6.6 - Flight Events

- Normal trajectory analyses should define the times of the key planned events of flight
- These events of flight are important to the overall FSA because they are associated with uniquely assigned
  - failure probabilities and failure rates
  - debris lists
  - flight safety system designs

Chapter 6 – Purposes of Normal Trajectory Analysis

Discussion

Floor open for questions/comments
Either verbally or via comments

Chapter 7 - Trajectory Simulation

Simulation elements

- Key elements to capture fundamental physics are:
  - Vehicle properties (mass, propulsion, and aerodynamic)
  - Environmental conditions
  - Guidance and control

Simulation implementation

- A 6DOF simulation is required
  - It is still a simplification of the real world

> - Simpler models are acceptable for smaller, unguided, rigid 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

- The software used for trajectory simulation should :
  - Have acceptance within the industry or use verified methods of 6DOF simulation
  - Be validated and tested (especially numerical implementation)

Section 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

Section 7.3 - Developing Vehicle Parameters

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)
  - Large control surface deflections and vehicle bending should be considered
- 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
- Uncertainties in propellant load and payload mass should be considered

Section 7.3 - Developing Vehicle Parameters

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
  - Controlled lift, asymmetry, and/or aero-surface control typically requires more complex data
  - 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 model should consider the entire flight regime from rarified atmosphere hypersonic to sea level subsonic

Section 7.3 - Developing Vehicle Parameters

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
- 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

Section 7.3 - Developing Vehicle Parameters

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
- 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

A failure of configuration management has led to several catastrophic events

Section 7.4 - Output Interval

- Normal trajectory state data should be output for use in subsequent analyses at short time intervals
  - Intervals 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
- The smallest dispersions:
  - Consider only uncertainty, not variability
  - Usually due to loss-of-thrust and on-trajectory breakup events
- The interval must be 1 second or less, per § 450.117(d)(4)
  - normally, 10Hz or greater frequency is used for nominal trajectories

Chapter 7 – Trajectory Simulation

Discussion

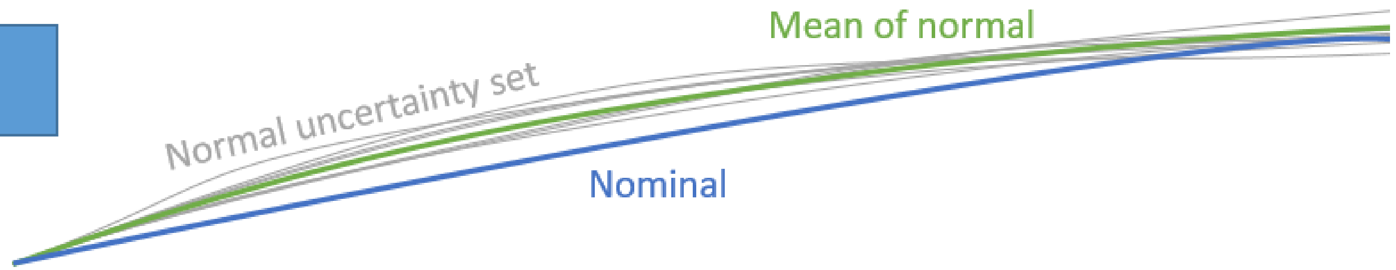
Floor open for questions/comments
Either verbally or via comments

Chapter 8 – Normal Trajectory Types

Nominal vs Normal Set (uncertainty) vs Variability

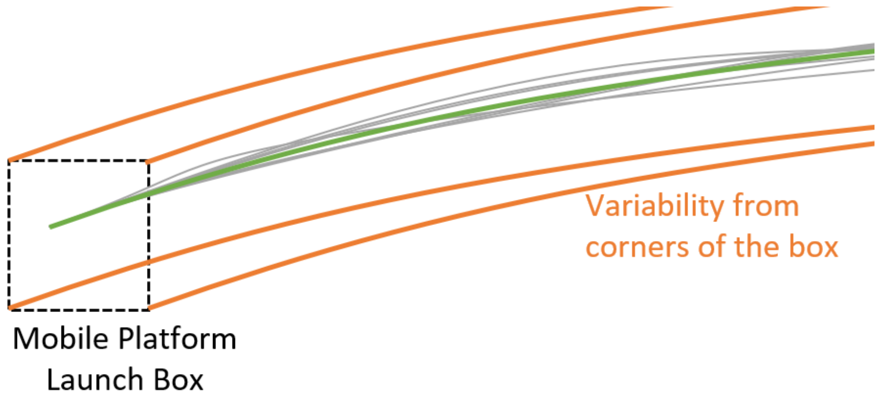
- A nominal trajectory is a single simulated trajectory of the launch or reentry vehicle where:
  - all vehicle aerodynamic parameters are as expected
  - all vehicle internal and external systems perform exactly as planned
  - no external perturbing influences other than the nominal atmospheric drag and gravity
- A set of normal trajectories:
  - aerodynamic parameters sampled across uncertainty ranges assigned to each flight performance or environmental parameter
  - often referred to as the set of "dispersed" trajectories

Nominal ≠ Mean of Normal



Section 8.2 - Variability vs. Uncertainty

- The term “variability” refers to factors that are not known in advance of initiating the launch or reentry operation but *will be known or could be known* with significantly lower uncertainty at the time the commitment is made to initiate the operation
- 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
- A flight safety analysis should demonstrate that **each trajectory in this set (**used to characterize variability), when treated as the planned flight, meets the risk criteria because a decision not to fly one of these trajectories *could be made* prior to initiation of flight



Section 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

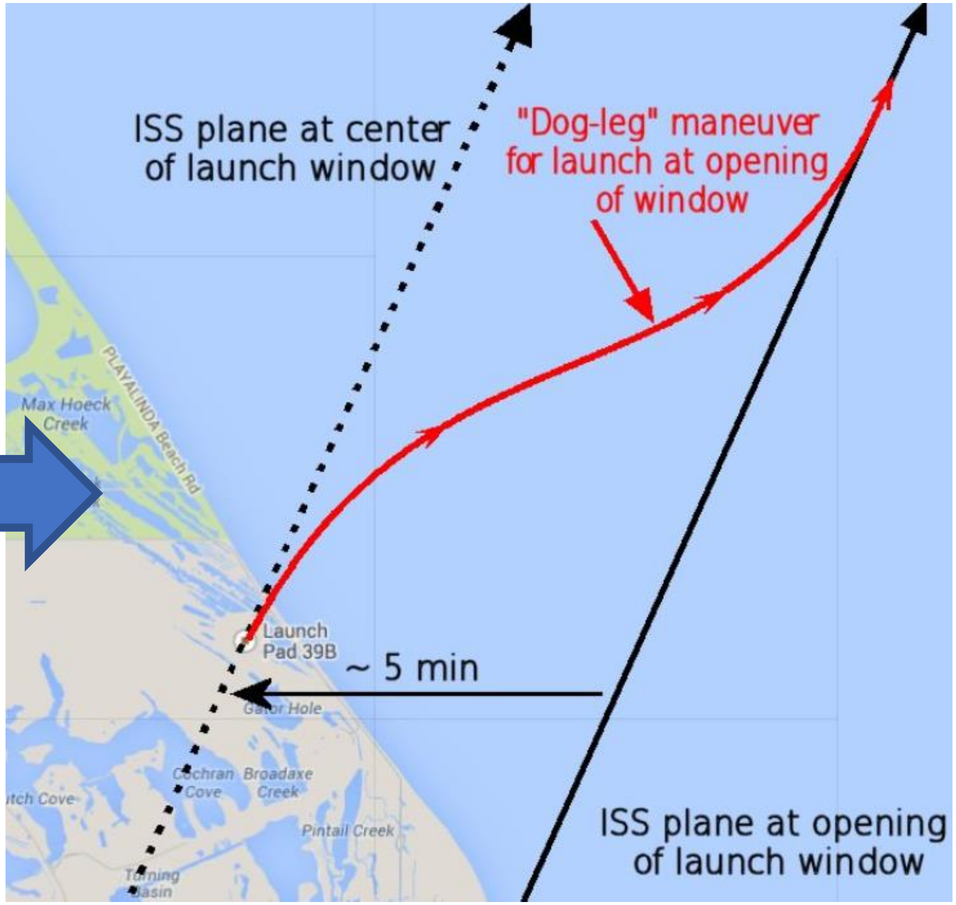
- The FAA considers “a significant influence” to include **any parametric uncertainties that affect the crossrange IIP location or downrange IIP rate by at least one percent** relative to the combined uncertainty of all parameters.

- The AC outlines a procedure to determine which parameters are significant

Section 8.4 - Normal Trajectory Set Due to Variability

Variabilities:

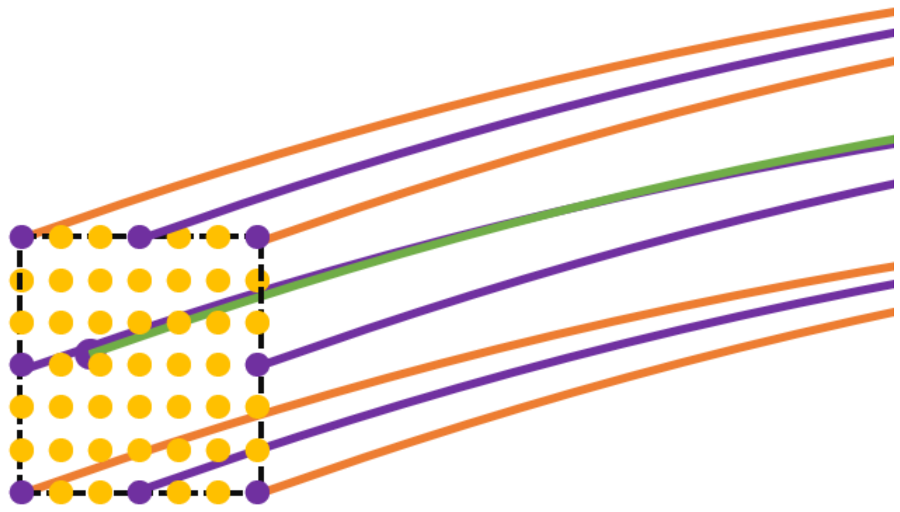
- Wind - A contributor to normal trajectory variations is the range of wind conditions that the vehicle will experience. For a controlled vehicle, guidance system logic will normally adjust the flight path of the vehicle to meet certain conditions
- Operation Window - For some missions, the trajectory that is flown may change significantly during the operation window.
- Platform Variability - When a mobile platform is used, such as a ship or an aircraft
- Other missions may have additional sources of variability



Section 8.4 - Normal Trajectory Set Due to Variability

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
- Additional intermediate trajectories may also be necessary to resolve relevant differences in risk



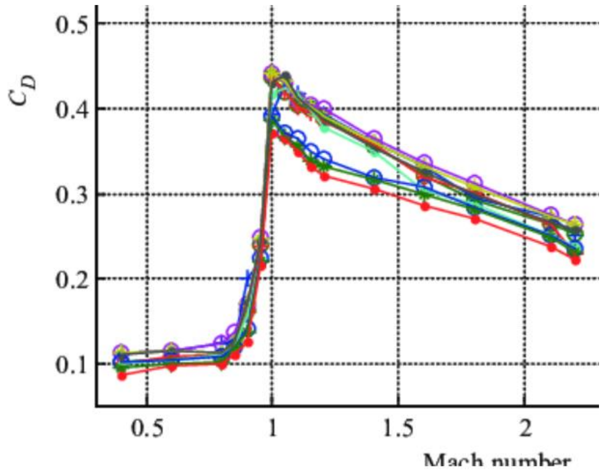
Section 8.5 - Normal Trajectory Dispersion Due to Uncertainties

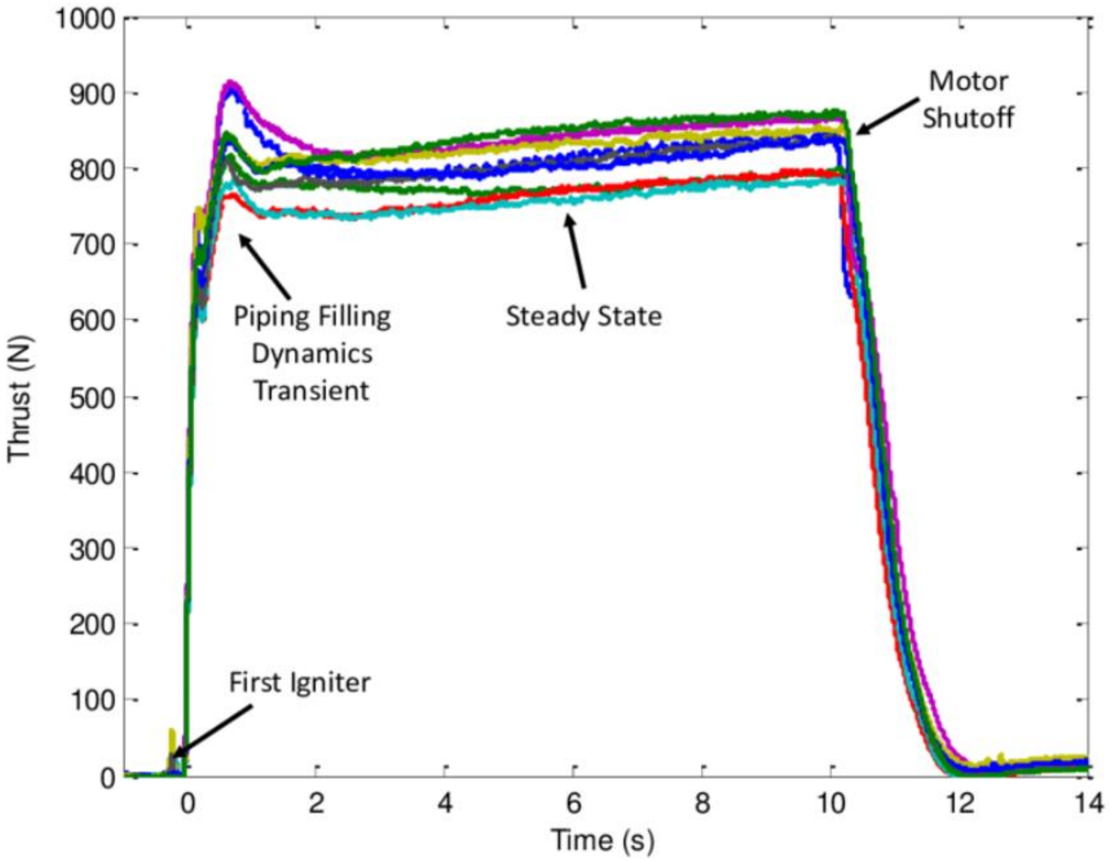
- A trajectory is a deterministic prediction of a launch or reentry profile that has inherent uncertainties that need to be evaluated in a statistical sense
  - The launch or reentry system itself has physical parameters that are not exactly known
  - The best estimates of uncertainty should be used, not exaggerating or over-stating in an attempt to be "conservative"
- For safety purposes, 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
- 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

Section 8.5 - Normal Trajectory Dispersion Due to Uncertainties

Sources of Uncertainty include:

- Motor Performance – Usually the most important
- Aerodynamic Parameters
- Mass properties
- Control System
- Navigation
- Environment



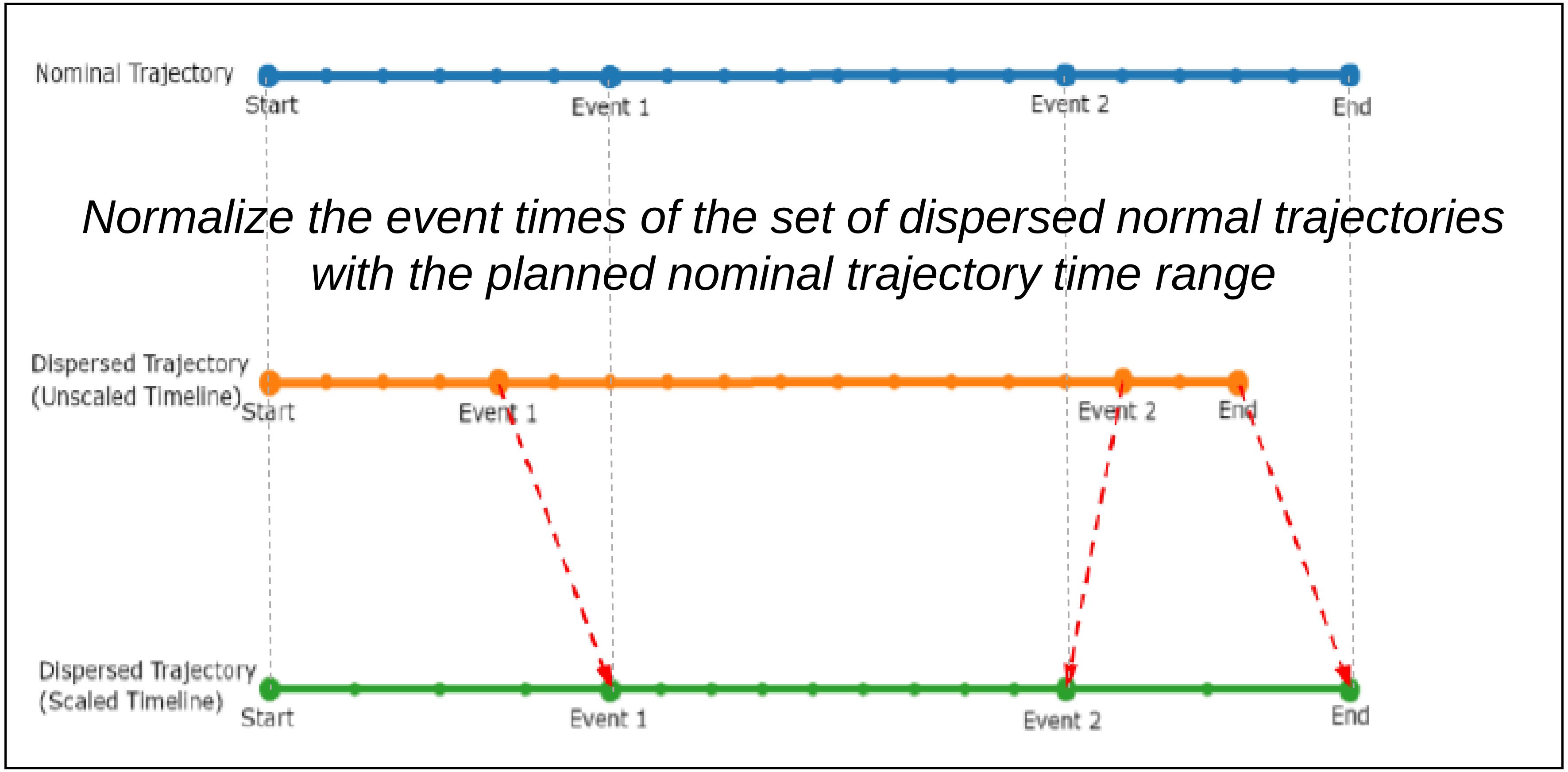


Section 8.5 - Normal Trajectory Dispersion Due to Uncertainties

- The state of the vehicle is more important than the flight time for many aspects of risk analysis

- Each state vector in a set of normal trajectories should be assigned a “nominal-equivalent time”

Normalizing Event Times on Normal Uncertainty Trajectories



Discussion

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Either verbally or via comments

Chapter 9 – Atmospheric Effects

- The nominal trajectory, the variability trajectory set (including worst conditions), and the uncertainty trajectory set(s) should use different sets of atmospheric data
- 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
- Wind and air density are most important
  - Wind *variation* is important in the launch and landing areas
  - Air density *variation* is important for shallow re-entry

Section 9.1 – Data Sources

- Global Data - The primary data source is the Earth-GRAM, which includes Range Reference Atmosphere data
- Historical Data - Historical and local data should be used to evaluate trajectory variability, including worst conditions -
  - Databases maintained by the launch or reentry site, and
  - NOAA Radiosonde database
- Forecast Data - For development of trajectories in the launch countdown, use atmospheric forecasts (GFS / NAM / Range)

Section 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
  - This reduces the likelihood of a failure due to aerodynamic effects
- Trajectory simulation should be performed for a large range of atmospheric profiles
- Mission rules should be established regarding flight acceptability based on the wind conditions

Chapter 9 – Atmospheric Effects

Discussion

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Chapter 10 – Satisfying Application Requirements

Section 10.1 – Methodology Description

A document should describe the approaches for the following:

- Simulation Software - technical description, validation, justification for the fidelity
- Data - control logic, vehicle data, and environmental data
  - Numerical simulation approaches (e.g. CFD)
  - Measurement approach for gathering data
- Process –
  - Configuration control
  - Identifying variability

Section 10.2 – Input Data for Trajectory Analysis

- Input data:
  - mass, aerodynamic, and propulsive properties
  - data input to the guidance program
  - atmospheric conditions used
- Format:
  - files that are input to the simulation program
  - document defining each data element
  - Uncertainties with distributions and parameters
- Scope:
  - Representative mission used for all data in the application
  - A subset is required for every mission per § 450.213(b)(2)

Section 10.3 – Worst Atmospheric Conditions

- Description of
  - the process for determining constraints
  - how the atmospheric conditions are evaluated during the launch countdown to assess whether the flight may proceed
- Quantitative data, either:
  - the worst case conditions acceptable for flight OR
  - the worst case conditions associated with the representative flight

Section 10.4 – Trajectory Outputs

- Provide trajectory data developed for a representative trajectory analysis:
  - Description of mission objectives and vehicle constraints that are assumed
  - 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)
  - The same analysis that would be performed in anticipation of that mission
- If a flight includes parallel flight segments, nominal trajectory data and both types of normal trajectory (variability and uncertainty) sets should be provided for all segments.
- Both tabular data as well as graphical visualizations of the data
  - No particular file format is recommended, but all trajectory submissions related to an application should be in the same format

Chapter 10 – Satisfying Application Requirements

Discussion

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Upcoming Workshops

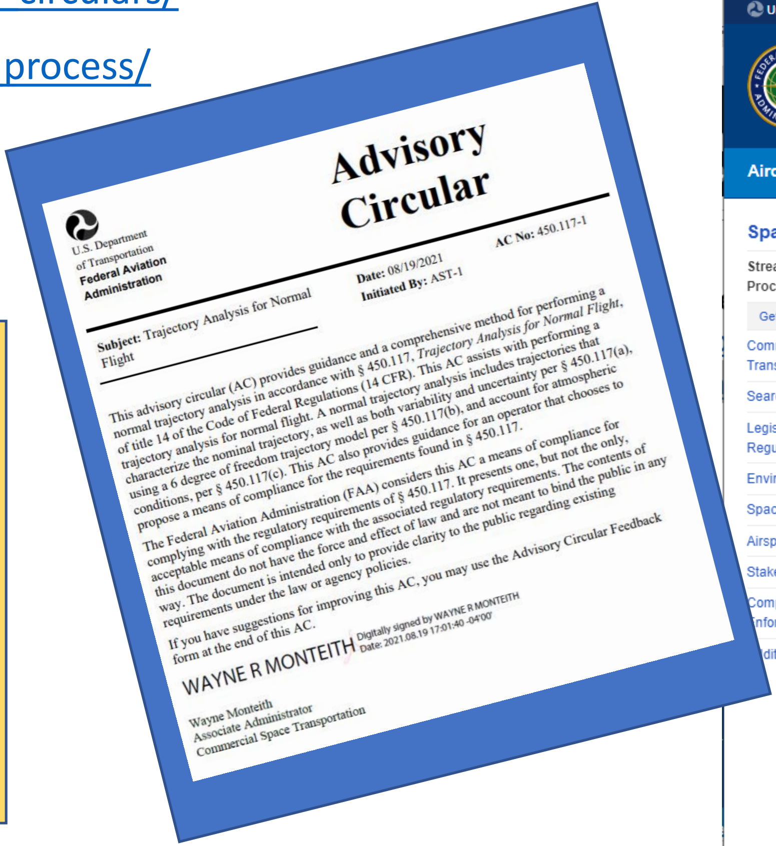
- September 23 @ 1400 Eastern time:
  AC 450.141-1 Computing Systems and Software
- Date/Time TBD (September/October):
  AC 450.173-1 Mishap Plan-Response, Reporting, and Investigation Requirements
- Date/Time TBD (September/October):
  AC 450.103-1 System Safety Program (https://www.faa.gov/regulations_policies/advisory_circulars/index.cfm/go/document.information/documentID/1040281)

Where to Find the ACs on AST Part 450 Webpages

Links to ACs:

https://www.faa.gov/regulations_policies/advisory_circulars/

https://www.faa.gov/space/streamlined_licensing_process/


U.S. Department of Transportation
Federal Aviation Administration

Advisory Circular

Subject: Trajectory Analysis for Normal Flight

Date: 08/19/2021
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

To ensure your comments and questions are considered in a future revision of the AC, please submit via the Feedback Form: https://www.faa.gov/documentLibrary/media/Form/FAA1320-73.pdf. Attachments to this form are welcome.

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Contact

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