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Range safety requirements and methods for sounding rocket launches

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ARTICLE INFO

Acronyms:

AIS	Abbreviated Injury Scale
BUSV	Break-up State Vector (position and velocity)
DOF	Degree of Freedom
FAA	US Federal Aviation Administration
NASA	US National Aeronautics and Space Administration
OT	On-Trajectory
RCC	US Range Commanders Council
RRAT	Range Risk Analysis Tool
TAOS	Trajectory Analysis and Optimization Software
US	United States
USAF	US Air Force

ABSTRACT

This article describes requirements and methods employed to ensure safety during sounding rocket launches. Sounding rockets are typically rail launched on suborbital trajectories with no active guidance systems; instead fins are used to stabilize the rocket by moving the center of pressure behind the center of gravity. Fins mounted at an angle to induce spin about the roll axis are a particularly effective means to maintain flight along the intended trajectory. This article reports on the application of high fidelity trajectory and debris impact dispersion analysis methods and launcher setting optimization techniques to prevent debris impacts outside of the predetermined hazard areas for multi-stage spin-stabilized sounding rockets. Accurate trajectory analyses, for nominal and malfunction conditions, are critical to the safety of sounding rocket launches, whether or not a risk assessment is performed. Therefore, a significant section of this article addresses requirements and methods for high fidelity trajectory analyses, including lessons learned from recent experiences. Examples are presented to demonstrate that a full 6DOF trajectory analysis is necessary to compute accurate impact dispersions for sounding rockets with significant angular momentum. The importance of angular momentum to the flight dynamics of a typical spin stabilized rocket highlights the desirability of a nominal impact dispersion analysis that uses the Monte Carlo technique to account for the non-linear effects of various combinations of input parameter perturbations, such as launch elevation and thrust angle, or thrust offset and thrust angle. This article also describes requirements and methods used for public risk management of sounding rockets, including risks to people in various transportation modes such as aircraft, ships, and automobiles. This article assesses generic types of sounding rocket anomalies, such as fin failures, motor case ruptures, or staging anomalies, and illustrates methods to address these types of events from a range safety perspective.

1. Introduction

This article focuses on range safety issues and techniques for sounding rockets: suborbital rockets that are typically rail launched and stabilized by fins mounted to induce spin about the roll axis. Targeting the intended impact location (i.e. the aim point) of a sounding rocket is accomplished by adjusting the launcher settings: the launch rail azimuth and elevation. The presence of significant winds, which often vary considerably at different altitude, makes adjustments to the nominal (no wind) launch rail azimuth and elevation necessary to prevent the rocket from landing too far from the aim point. Containment of the potential impact points is a primary goal of range safety. However, in many instances complete containment within an unpopulated area is not feasible, even in the absence of a malfunction. Therefore, a risk assessment is often performed to ensure that the threat posed by launch is within acceptable limits. In addition, the launch risk assessment process often reveals risk mitigations that can readily enhance safety without compromising the mission goals. This article describes high-fidelity trajectory computations used to compensate for wind effects, define nominal impact dispersion areas, and estimate potential responses to various malfunctions. This article also presents in flight risk assessment standards and methods used for typical spin stabilized unguided multi-stage rockets.

2. Trajectory and wind analysis

“Wind weighting” refers to the process of determining a launcher setting that compensates for the prevailing winds. During the countdown prior to launch, winds are measured and a launcher setting computed to target the aim point. Wind weighting is the primary means of vehicle containment for a sounding rocket that lacks a flight termination system. Optimization techniques incorporated into the Trajectory Analysis and Optimization Software (TAOS) developed by Sandia National Laboratory are ideally suited to wind weighting. ACTA

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developed an interface (called WinTAOS) that facilitates the development of TAOS input and analysis of the output from TAOS.

Wind produces two types of effects on an aerodynamically stable sounding rocket depending on whether it is thrusting or not: weathervane turning and drift. The FAA considers an aerodynamically stable rocket as one where the center of pressure (where the net force due to atmospheric forces acts) is at least two calipers (i.e. rocket diameters) behind (i.e. farther from the nose of the rocket) than the center of gravity. An aerodynamically stable vehicle that is thrusting will always turn into the wind, like a weathervane. This weathervane effect also turns the thrust vector of the vehicle resulting in vehicle translation into the wind. For example, a tail wind (coming from the back azimuth, opposite of the intended direction of flight) will tend to pitch a thrusting rocket up, so that the rocket turns to fly toward the back azimuth direction. Therefore, the weathervane effect cannot be modeled adequately with strictly a three degree of freedom (3DOF) analysis, where the rocket orientation is not modeled. However, an approximate 3DOF analysis can be made based on an assumption that the rocket responds instantly to maintain zero angle of attack. Of course, a vehicle without thrust tends to drift in the direction of the wind due to atmospheric drag.

A sounding rocket is most susceptible to the weathervane effect while the rocket velocity is low (i.e. when the wind speed is a significant fraction of the rocket's airspeed). A sounding rocket that accelerates quickly, and thus exits the rail with a relatively high velocity, will help minimize the nominal impact dispersion area. Similarly, a long rail will help keep the actual impact point close to the nominal aim point. Spin motors are sometimes used to provide a high roll rate soon after the rocket exits the rail, and thus reduce the nominal impact dispersion area. Spin stabilization (angular momentum) can have an important effect on the characteristics of the nominal impact dispersion area as discussed below.

The weathervane effect is often the dominant uncompensated wind effect on a sounding rocket, resulting in a net translation into the wind relative to the nominal aim point. Thus, wind weighting using a 3DOF analysis during the thrusting portion of flight will not provide high-fidelity results for range safety purposes. Therefore, 6DOF input data and analysis, accounting for the rocket orientation, may be necessary to ensure safety. Range safety should independently develop and/or verify the input data used for wind weighting.

3. Nominal impacts and hazard areas

Since operational sounding rockets have over a 95% demonstrated reliability,[1] a launch failure resulting in impact outside of nominal impact dispersion (often defined to provide 99.7% confidence of containment of the ground impacts from a nominal launch) area is relatively unlikely [1]. Therefore, a valid nominal impact dispersion analysis is vital to range safety to define debris impact hazard areas. Additionally, most sounding rocket failures do not involve extreme trajectory deviations (relative to the nominal trajectory dispersions), so most failures are likely to produce debris impacts within the nominal impact dispersion area. This section presents methods that have been successfully applied to quantify nominal impact dispersion areas, and some lessons learned about the influence of sounding rocket characteristics on the nominal impact hazard areas. Key lessons learned include the following.

1. The size and shape of a nominal impact dispersion area for a sounding rocket is sensitive to many parameters and their uncertainties. Therefore, range safety should independently develop and/or verify the input data and results used to define nominal impact hazard areas.
2. The Monte Carlo technique is ideally suited for nominal impact dispersion computations because of the non-linear effects of various combinations of input parameter perturbations, such as launch elevation and thrust angle, or thrust offset and thrust angle.
3. The characteristics of nominal impact dispersion areas for sounding rockets are highly dependent on numerous parameters. No single probabilistic distribution is adequate for range safety purposes in all cases; for example, significant changes in the nominal elevation for the same rocket can substantially change the size and shape of the nominal impact dispersion areas predicted using high-fidelity trajectory simulation techniques.

Normal variations in rocket performance, and typically to a much lesser extent, errors in wind measurements and wind weighting methods, often lead to a significant nominal impact dispersion area. This section reviews results from a rigorous method to perform a nominal dispersion analysis using TAOS for a typical two-stage unguided spin stabilized (sounding) rocket and discusses the development of nominal impact hazard areas.

The author performed a nominal trajectory analysis for the Talos-Castor using TAOS with data input that consisted of (1) an independent 6DOF input data set developed by Sandia National Laboratories for the Talos-Castor using wind tunnel test data and analysis, and (2) thrust profile, payload weight, and critical event time data developed for different specific missions. The position and velocity output from TAOS matched the data from the launch provider within about four percent for several key times (burnout of each motor, apogee, and payload impact), with one exception. The TAOS results had a much higher impact velocity, presumably because the aerodynamic data from Sandia assumed the nosecone remained attached throughout the entire flight.

The author also performed independent nominal trajectory dispersion analyses using TAOS in a 6DOF mode and the Monte Carlo feature to account for all possible interactions between the perturbed parameters. Probability distributions were used to account for uncertainties in each of the critical input parameters, consistent with those used by NASA's Wallops Flight Facility for their launches of rockets that are built to comply with US military specifications.

Fig. 1 is a plot of 1000 nominal impact points computed by TAOS to simulate a mission that used spin motors that provide a positive roll in the right hand sense (i.e. clockwise when viewed from the tail). Fig. 1 shows that the major axis of the impact dispersion pattern is not parallel to either the downrange or cross range directions. Instead, the major axis of the impact dispersion pattern in Fig. 1 appears to be rotated by about 60° counterclockwise from the downrange direction. This result is due to the importance of angular momentum to the flight dynamics of this Talos-Castor launch that used spin motors. Specifically, thrust angle perturbations are the dominant source of dispersion for nominal Talos-Castor launches, which is generally true for many suborbital rockets. When the rocket has positive roll in the right hand sense, a thrust perturbation that will tend to push the rocket farther downrange (i.e. pitch down immediately after exiting the launch rail) will also veer to the left due to the gyroscopic effect (Newton's 2nd law applied to angular momentum). Similarly, when the rocket has positive roll in the right hand sense, a thrust perturbation that will tend to push the rocket up range (i.e. pitch up immediately after exiting the launch rail) will also veer to the right due to the gyroscopic effect. The Monte Carlo simulation simultaneously accounts for other sources of dispersion, including an independent thrust offset (vice thrust angle), such that some impacts farther downrange than the nominal can be off to the right, etc.

Fig. 2 is a plot of 1000 nominal impact points computed by TAOS for same input conditions as Fig. 1, but with simulated spin motors that provide a negative roll in the right hand sense (i.e. counterclockwise when viewed from the tail). Notice that the major axis of the impact

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[1] Between 1959 and 1999, the NASA sounding rocket program launched approximately 2,800 missions with an overall science mission success rate exceeding 86 percent and a launch vehicle success rate of over 95 percent.