Development of a Handbook for Astrobee F Flight-Performance Predictions

Robert S. Wolf*

Massachusetts Institute of Technology, Cambridge, Massachusetts

Abstract

A HANDBOOK for performance and stability analysis of the Astrobee F sounding rocket was developed.[1] The handbook included sections on performance, stability, and roll rate. Parameters affecting vehicle performance were identified and their relative effects assessed. Predictions of several flights were made and compared to measured flight data. Predictive accuracy within 2% was consistently obtained. Next, a technique was developed to quickly determine if a given payload would yield a vehicle with adequate stability for flight, based on a rigid body static margin requirement. Finally, a simple technique was developed to estimate fin cant angles required to achieve a specified burnout roll rate. By following the method outlined in this paper, one could create a similar handbook for any sounding rocket series.

Contents

The paper discusses the development of the handbook as well as its applications and limitations. The handbook is divided into three sections: performance, stability, and roll rate. The performance section provides information on altitude, Mach number, dynamic pressure, and velocity as functions of time from launch at each of two launch sites (White Sands and Churchill). The stability section shows whether a vehicle with a given payload will have a rigid body static margin of at least 8% of total vehicle length at all times during flight. If not, the same graphs can be used to determine the amount and location of ballast required to meet that stability criterion. Finally, the roll rate section shows the fin cant angle required to achieve a burnout roll rate of 2.5 cycles per second.

The effect of the following vehicle characteristics were considered within the ranges specified:

1) payload weight (400-800 lb);
2) payload length (130-250 in.);
3) payload diameter (15 or 17.26 in.);
4) nose shape (cone or ogive);
5) number of fins (3 or 4).

The effect of variations of the above parameters on performance was determined by analyzing the resultant changes in apogee. This simplification was justified by realizing that time-above-altitude (which directly relates to apogee) is the prime requirement for many experimenters. The MASS program[2] provided the three-degree-of-freedom (DOF) trajectory predictions that were the basis of the investigation and of the handbook itself. Aerodynamic data for the trajectory computations came from the TAD[3] program and an unpublished program for drag predictions.

Of the aforementioned parameters, payload weight had the greatest effect on performance. Therefore, the final performance time-histories presented in the handbook included payload weight as an independent variable (Fig. 1). Payload diameter and fin quantity had distinct effects which were handled by presenting separate performance graphs for each configuration.

Payload length had a minor effect on performance. Changing the length of a nonbulbous (15-in. diam) payload by 50 in. only changed the apogee by 1%. The effect was even smaller for bulbous payloads, since the skin-friction drag is a smaller percentage of total drag for these vehicles. Nonetheless, the effect of payload length was included in the handbook. A payload of a given weight was assumed to be a certain length that was based on an analysis of previous payloads. Performance data were calculated at that payload length for presentation, as in Fig. 1. The performance was then recomputed using different lengths to determine the percent change in apogee per inch of payload length change, which was presented as a correction graph.

The nose shape had a negligible effect on performance. A test case was run on a 17.26-in. payload diameter, 4-fin vehicle at several payload weights. The apogee predicted with a 3:1 ogive was compared to that predicted with a 3:1 nose cone. The maximum difference was 0.17%. Since the apogee difference was so small, all performance predictions assumed a nose cone.

The accuracy of performance predictions was assessed. Apogees were predicted for twelve flights and compared to ac-

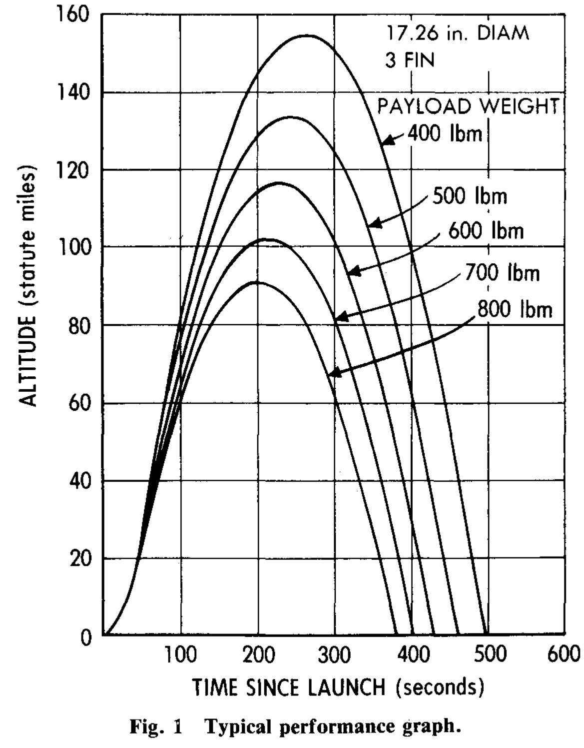

Fig. 1 Typical performance graph.

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*Research Associate, Space Systems Laboratory; formerly Flight Performance Engineer, NASA/GSFC Sounding Rocket Division. Member AIAA.

tual measured apogees. The mean error was 0.05%, with a standard deviation of 1.76%.

Stability

To be assured of sufficient stability for flight, the NASA Sounding Rocket Division required Astrobee F's to have a predicted rigid-body static margin (RBSM) of at least 8% of the total vehicle length. Simply stated, the static margin of stability is the distance between the center of pressure (CP) and the center of gravity (CG).

Time histories of CP and CG were required to calculate the static margin. The CP time history was created by combining a CP vs Mach number curve with a Mach number time history available from the performance section. A CG time history of the vehicle minus the payload was readily available. Thus, for a given payload configuration and weight, it was possible to calculate the payload CG that would result in a vehicle whose RBSM would reach a minimum of 8% at some time during flight. In this manner a stability boundary for payload CG could be derived.

A family of curves which showed the aftmost allowable payload CG as a function of payload weight and length (Fig. 2) was generated for each configuration. These curves served as a quick check on whether a given payload would result in a vehicle that was sufficiently stable for flight.

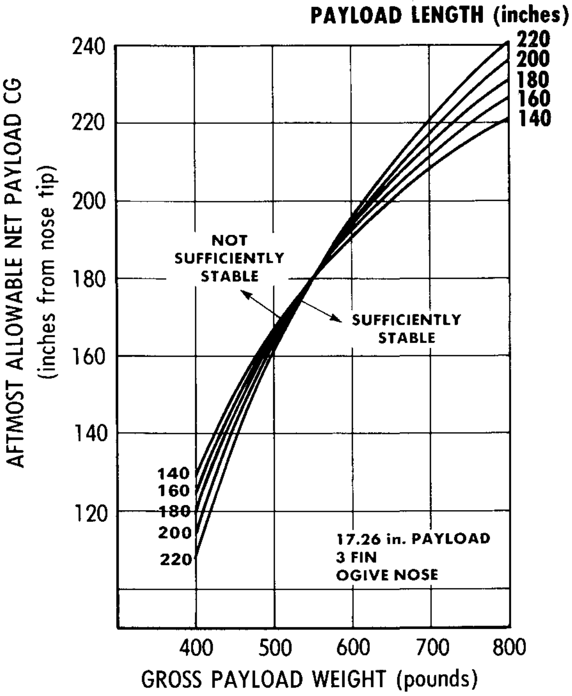

Fig. 2 Typical stability boundaries.

Roll Rate

NASA guidelines called for Astrobee F's to have a burnout roll rate of 2.5 cps. Unfortunately, Astrobee F roll rates have varied considerably from predicted values, with no specific cause identified.[4] However, analysis of 5-DOF trajectory predictions for several flights revealed that the predicted burnout roll rate was 72-78% of the steady-state roll rate, under the conditions at burnout. Therefore, the handbook recommended fin cant angles to achieve a 2.5-cps burnout roll rate, based on attaining 75% of the steady-state roll rate.

The equation for steady state roll rate P is

$$P = -C_{l_\delta}\delta 2V/C_{l_p}d \tag{1}$$

where C_{l_δ} and C_{l_p} are the roll driving and roll damping moments, respectively, δ is the fin cant angle, V is velocity, and d is a reference diameter (1.25 ft for the Astroee F). If we set P-3.33 (which is 2.5/0.75) $V-V_{bo}$ (burnout velocity), and solve for δ, we get

$$\delta = -\frac{3.33\ \text{cps}}{(C_{l_\delta}\ 2V_{bo}/C_{l_p}d)} \tag{2}$$

Hence, for a given vehicle, the required fin cant angle is a function only of burnout velocity and the ratio of roll driving and roll damping moments (C_{l_δ}/C_{l_p}).

Analysis of aerodynamic data revealed that the ratio of C_{l_δ} to C_{l_p} is nearly constant with Mach number, even though the coefficients themselves vary considerably. In the Mach number range from 4.5 to 7, which encompasses the entire range of burnout Mach numbers, the ratio varies by only 3%. Additionally, the ratio is independent of the number of fins, even though the coefficients themselves are proportional to the number of fins.

Given this discovery, the required fin cant angle was reduced to a function of burnout velocity alone (Fig. 3).

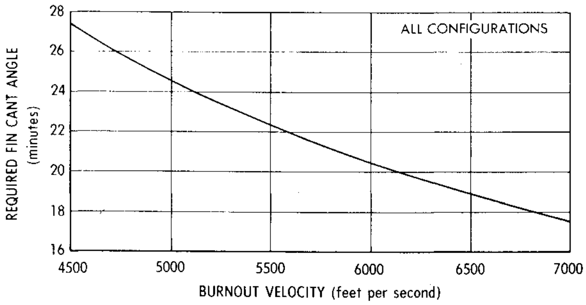

Fig. 3 Fin cant angle required for 2.5 cycle per second burnout roll rate.

References

[1] Wolf, R.S., *Astrobee F Performance and Stability Prediction Handbook*, NASA/GSFC, Sept. 1978.

[2] Anon., *Missile and Satellite Systems Program*, General Electric Company.

[3] Barrowman, J.S., "An Improved Theoretical Aerodynamic Derivatives Computer Program for Sounding Rockets," AIAA Paper 79-0504, AIAA 5th Sounding Rocket Technology Conference, March 1979.

[4] Shell, A., *Roll Rate History Data for Astrobee F Flights 25.013, 25.020UG, and 25.025UE*, TM-79/6118, Computer Sciences Corporation.