INTEROFFICE MEMO AEROJET-GENERAL CORPORATION

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SUBJECT: Standardized Perturbation Values for Several Sounding Rockets to be Used in the Calculation of Dispersion and Structural Loads

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1. SUMMARY

As part of an effort to generate dispersion-time histories for several sounding rockets, a review of the perturbation levels previously employed at Space General was completed. This review considered numerical values used in both loads and dispersion analyses. Where possible, experimental averages were constructed and compared with existing numbers. Where appropriate, improved estimates were determined and are presented.

2. RECOMMENDATIONS

First, perturbation values for all sounding rockets in service should be reviewed, and updated on an annual basis by Systems Engineering. In addition, a review of perturbations by Systems Engineering for a specific sounding rocket should be the first step in any loads or dispersion analysis. Second, Systems Engineering should maintain a central file containing both current and historical perturbation data, and the sources of such data.

3. INTRODUCTION

The perturbations presented in this document are based on three principles:

a) All analyses for a given rocket should be based on a set of internally consistent numbers. The numerical values of a specific perturbation employed in the analysis of dispersion, coning, loads, etc. of a given rocket should all be the same. If this is not done we can be certain that at least one of any two analyses based on conflicting numbers is incorrect.

b) All vehicle perturbations should be presented in the same format. This format must be defined in detail, and the definition circulated among the appropriate users of data. The only alternative is confusion, misunderstanding and, ultimately, error.

Unless specifically noted to the contrary, all perturbations are normally distributed random variables with zero mean. The tabulated numbers in the following section are standard deviations. For those variables which have two orthogonal components, the tabulated values represent the standard deviation of amplitude. It is always assumed for such variables that the same physical process acts independently in the two orthogonal planes.

c) The third principle is that the numerical values of the standard deviations used for analysis should not conflict with experimental evidence. As a corollary to this, perturbing effects may be expected to show similar non-dimensional values for similar sounding rockets.

4. DISCUSSION

Table I summarizes the results of the present perturbation analysis for the vehicles listed. It will be noted that perturbations appear in three distinct classes, i.e.,

I) Non-Vehicle Errors

II) Variations in Specific Energy

III) Body-Fixed Perturbations

Table II is a compilation of relevant historical perturbation data for various SGC sounding rockets. Included are the date and report from which the data were taken.

The estimation of the magnitudes of various perturbations is explained in subsequent sections; these will be taken in the order in which they appear in Table I. It should be noted that Table II is included for historical reasons only.

4.1 NON-VEHICLE PERTURBATIONS

Class I (Non-Vehicle) perturbations include those effects which may contribute to an uncertainty or a change in the initial state vector. These include:

a) Ballistic wind errors
b) Launcher alignment errors
c) Launch time errors
d) Launch coordinate uncertainty

It can be seen that this entire class of errors is largely independent of a vehicle selection, and dependent upon the launch location and choice of launcher hardware.

For the analysis of loads, the wind gust amplitude standard deviation is 6.11 feet per second. The altitude covariance constant is 0.00343 radians per foot. See Ref. (1).

The ballistic wind error is the greatest single source of dispersion in most sounding rockets. It is due to several independent factors, the greatest of which is probably time delay between wind measurement and vehicle launch.

The wind data from References (2) and (3) represent the best current estimate for standard deviation of ballistic wind within the ZI. These figures have been averaged to produce the recommended value of 4.49 ft/sec.

Wind variability shows marked dependence on both launch site and season; where available, more specific data should be employed.

Launcher alignment uncertainties are due mainly to loss of precision in the measurement of launcher pointing angles, as well as errors in relating actual vehicle initial conditions to launcher settings. Also included are static and dynamic effects due to missile/launcher loads and nominal clearances, and tipoff effects due to non-simultaneity of launch constraint release.

Launch time uncertainties do not contribute to vehicle impact point dispersion, but do influence the error in knowledge of the vehicle state at a known universal (Z) time. If vehicle dispersion relative to some independent event (such as another vehicle nominal position or a geophysical event) is not required, this factor may be ignored.

Launch coordinate uncertainty is generally several orders of magnitude less than the other effects, and is usually ignored. It must be considered, however, when launching from mobile or unsurveyed sites.

4.2 ENERGY PERTURBATIONS

Class II (Energy) perturbations cause first-order variations in the vehicle specific energy, and some second-order effects in flight path angle and wind response.

Their effect on impact point dispersion is almost exclusively in the inrange direction, with very small cross-range contributions due to the effect of the earth's rotation.

The contribution of energy errors to spatial dispersion is felt in both the inrange and altitude coordinates.

Specific energy perturbations include uncertainties in:

a) Drag
b) Delivered specific impulse
c) Propellant weight
d) Inert components' weight
e) Net payload weight
f) Stage ignition time

Drag variation on a round-to-round basis is due to:

a) Atmospheric variations
b) Uncertainty in C_D estimate
c) Vehicle dimensional variations
d) Simplification of drag model
e) Minor configuration changes

The effect of atmospheric variations has been evaluated from data in Ref. (4). A standard deviation for density averaged over all seasons for the ZI indicates a drag variation of ± 1.8%.

Uncertainty in C_D estimates is due to the basic uncertainty associated with all aerodynamic phenomena. This contribution is estimated at ± 5% for configurations with some flight history, and ± 10% for new vehicles.

Vehicle dimensional variations are small, estimated to contribute ± 0.2% to the drag variation.

Modeling errors include the contributions due to varying Reynolds number and boundary layer to wall temperature ratio over the flight profile, and are estimated to cause ± 1.0% variation in the nominal drag.

Configuration uncertainty includes such items as the addition of antennas, umbilicals, payload access doors, changes in launch lugs, etc. This effect is estimated to contribute an additional ± 2.0% drag uncertainty, except where the payload is shrouded (as in the Astrobee 1500); there the effect is negligible, since the external configuration remains unchanged by payload configuration changes.

Delivered specific impulse errors are dependent upon variations in:

1. Propellant specific impulse
2. Atmospheric and regulator pressure
3. Propellant conditioning temperature
4. Motor dimensions
5. Modeling errors

The delivered specific impulse variation for the Aerobee liquid sustainers can be estimated from static test data. Ref. (5), Appendix B cites 50 examples of Aerobee 150 static test determinations of characteristic velocity. This parameter is proportional to specific impulse, and depends on exhaust gas composition. The variation in characteristic velocity can be attributed almost exclusively to delivered specific impulse variations, and as such, results in a ± 2.2% variation for single thrust chamber liquid sustainers.

The Aerobee 350 employs four thrust chambers; if these acted independently, a coefficient of variation equal to $1/\sqrt{4}$ of that for a single chamber would be expected. This results in an estimated coefficient of variation on I_{sp} of 1.1%. The variation of delivered specific impulse for solid-propellant motors was estimated using data from TE-388 Iroquois static tests. These tests encompassed a range of conditioning temperatures, atmospheric conditions, and spin rates. The resulting variation in I_{sp} was 1.1%. This figure includes performance program modeling errors such as I_{sp} dependence on spin rate acceleration, and temperature.

Propellant weight uncertainty is due to variations in:

1) Case/tankage volume
2) Propellant specific gravity
3) Sliverage losses

The combined effects of items (1) and (2) on case bonded propellant grain weights is estimated at ± 0.9% from Iroquois data, and for uninhibited solid grains at ± 0.3%.

The effect of tank volume uncertainties on liquid sistainer propellant weights is estimated at ± 0.4%, and liquid propellant specific gravity variations are estimated to produce another ± 0.6% variation in propellant weight.

The effect of sliverage was evaluated for the NIKE booster only, using the data presented in Reference (5), P56. This effect results in an additional ±0.96% uncertainty in NIKE propellant weight change.

Evaluation of flight data for 203 Aerobee 150 and 150A vehicles shows an apogee altitude (or energy) variation of ±5.0%. This can be explained by a sustainer propellant residual at the time of fuel or oxidizer depletion combined with other energy perturbations. This residual is due almost entirely to mixture ratio variations, which were shown in Reference (5) to average ±6.5% for static test data. The mixture ratio variation required to reconcile estimated with observed apogee variations is ±4.0%, and this results in a ±1.15% weight change variation for single chamber sustainers, and a ±0.57% variation for the Aerobee 350.

Inert components weight variations are due mainly to manufacturing tolerances, and are in general, independent of other errors. Some correlation can be expected between inert parts variations and propellant weight variations for liquid sustainers and case-bonded solids, but this correlation is expected to be less than 0.2, and can be ignored.

Actual, unpublished, weight data are available for Aerobee 150's, and actual published data for Aerobee 350 sustainers are in Reference (6). These data result in a weight uncertainty of ±0.5% for 150/170 sustainers and ±0.6% for 350 sustainers.

Data from Iroquois static tests indicated a value of ±0.7% for inert parts weight variation.

Net payload weight is generally well determined at the time of payload integration with the rocket vehicle. Variations in this figure are due to weighing accuracy and uncontrolled payload changes. This effect is estimated to result in a ±0.3% variation in payload weight.

Stage ignition time variations are due to ignition timer uncertainties, mechanical (lanyard) tolerances, and starting transient. The effect on lanyard initiated liquid sustainers is considered negligible, and the effect of an estimated ±1.0% timer error overshadows ignition transients for the Astrobee 1500 upper stage.

4.3 BODY FIXED PERTURBATIONS

A. Fin Misalignment

The basic fin misalignment definition employed here is the angular error in effective setting between one fin panel and the fin shroud or tail can. To find the effective total cant error in roll for a complete rocket, it is necessary to RSS together the errors for all fins. For example, for the four-finned Aerobee 170, the standard deviation in fin cant, effective in roll, is

$$0.105\sqrt{4} = 0.21 \text{ deg} \qquad (1\sigma)$$

using the data of Table 1. To obtain the pitch/yaw error for a one-finned lift slope, we RSS the effects of the cant angle errors for the two fins, plus the independent effect on both fins of the joint between the tankage and tail can:

$$\sqrt{(0.105)^2(2) + (0.03)^2(4)(1/2)} = 0.1544 \text{ deg} \qquad (1\sigma)$$

also based on the data of Table 1.

This suggests a procedure for finding the fin alignment errors from flight roll rate data. A linear regression analysis has been made in which a model of the form

$$\delta = K\frac{P}{V}$$

is fitted. From this is found the "best" value for K, and the standard deviations in δ and $\frac{P}{V}$. Conversely, if good estimates for V and K are known, the standard deviation of δ can be easily found from the standard deviation in roll rate.

This procedure has been followed for the Aerobee 150A, which has the same sustainer fins as the Aerobee 170. Unpublished data for 16 Aerobee 150A flights was used. The Aerobee 170 fin error which resulted was 0.105 deg. per panel.

The Aerobee 150 sustainer tail assembly was evaluated using the data for 15 flights as reported in Reference (7). The error per panel was found to be 0.047 deg. The data from the much larger sample of 124 flights reported in Reference (8) was also processed. This gave a fin error of 0.063 deg. per panel. The difference in error values arises from the fact that there were some unusually large errors associated with a few flights in the Reference (8) sample. Since no explanation for these discrepancies was ever found, they may well reoccur in the future. The figure to be used is therefore taken as 0.063 deg. per panel.

The Aerobee 150 booster fins were assumed to be similar to the sustainer. Estimates for other fin panels are based on the Aerobee 150A data above, and a very similar result, unpublished, for the NIRO second stage. A value of 0.1 deg. per panel has been assigned pending experimental revision.

B. Body Joint Angular Error

The joint error reported here is based on unpublished data supplied by J. P. Taylor. His conclusion, based on accumulation of drawing tolerances for the Astrobee D, is that a radial screw joint has a maximum rotation error of 0.05 deg. This is due to all relevant errors having the same roll phase, and lying at the amplitude limits specified by the drawings. Assuming a rectangular distribution, the amplitude standard deviation, per joint, is

$$\sigma = \frac{(0.05)(2)}{\sqrt{12}} = 0.02887 \text{ deg.}$$

In the absence of more refined data, an assembly rotation error of 0.03 deg. per joint has been assumed for all sounding rockets.

C. Thrust Misalignment

The thrust misalignment values reported here are those numbers which give the approximately correct pitch/yaw moments for matching flight dispersions. Unpublished shop measurements of cold, unpressurized, quasi-thrust misalignments for twenty-five each Aerobee 170 and Aerobe 150 (M1) sustainers were examined. The resulting standard deviations were 0.0286 deg. and 0.0108 deg. for the 170 and 150 respectively. When some consideration for the effects of gas malalignment, pressurization, etc., is made, it was felt that the value of 0.0625 deg. used for many years was, if anything, slightly on the high side. The 0.0625 deg. figure has been retained. All other thrust misalignment numbers have been taken from References (9) through (12). In the case of conflicting numbers for the same motor, best judgement was used to select a common value.

D. Static Unbalance

In Reference (13) the data for the center of gravity offset of thirteen Aerobee 150 sustainers, less payload and fins, is presented. In lieu of more data, it was decided to consider the 150 figure representative of all sounding rocket hardware. The result shown in Table 1 is a one sigma lateral displacement of the center of mass relative to the external aeroshell as a fraction of the roll radius of gyration.

E. Product of Inertia

The product of inertia error is also obtained from the data of Reference (13) by a very similar process. Again, finless Aerobee 150 sustainer data is assumed, in the absence of further data to be representative of all sounding rocket hardware. The scaling to other configurations is as a percentage of $M K_r K_p$, an argument based on the definition of the product of inertia.

The conversion to a principal axis misalignment follows a straight forward procedure:

$$\sigma_\epsilon = \frac{\sigma_J}{M\,(K_p^2 - K_r^2)}\ \text{, or}$$

$$\sigma_\epsilon = \frac{0.0192\, K_r\, K_p}{(K_p^2 - K_r^2)}\text{, where}$$

K_r, K_p = roll and pitch radii of gyration, feet,
M = mass, slugs, and
σ_ϵ = standard deviation in the angle between the principal axis and the axis of symmetry of the external aeroshell, radians.
σ_J = 1 sigma product of inertia, slug feet squared.

It is usually found that σ_ϵ will vary roughly as the reciprocal of the fineness ratio.

F. Other

The major perturbing effect for the four vehicles discussed here which has not been described further is Astrobee 1500 second-stage "tipoff." The "tipoff" error budget in Reference (11) includes residual motion from the first stage perturbations, diaphragm hang-up, and interstage misalignment. With the current flight hardware, there seems to be little justification for retaining diaphragm hang-up as a dispersion source. The first stage residual motion should still be included in a dispersion analysis, but not as a tipoff effect. While an interstage misalignment is also still present, it would seem that the eleven minute figure quoted in Reference (11) is probably too high. It is recommended that the joint tolerance figure given earlier be used to compute a new interstage misalignment.

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TABLE I

"Summary of One Sigma Perturbations to be Used for Dispersion & Loads Analyses. All are Independent and are for the Circular Amplitude."

	Non-Vehicle Effects			Energy Errors						Body-Fixed Perturbations				
Vehicle & Stage	Ballistic Wind Ft/Sec	Launcher Pointing Error, Deg.	Drag Uncertainty, %	Ignition Time Error, % of Nom.	Specific Impulse, % of Nom.	Propellant ** Weight Loaded, % of Nom.	Weight ** Change % of Nom.	Inert ** Weight, % of Nom.	Payload Weight, % of Nom.	Fin Mis-alignment, Deg. per Fin Panel	Angular Error, Deg. per Joint	Thrust Mis-alignment Angle, Deg.	C.G. Offset % of K_r *	Product of Inertia % of $MK_r K_p$ *
Aerobee 150 (M1) VAM 20, Booster	4.49	0.125	5.8	0	1.1	0.9	0	0.7	0.3	0.063	0.03	0.05	1.25	1.92
Aerobee 150 (M1) VAM 20, Sustainer					2.2	0.6	1.15	0.5		0.063		0.0625		
Aerobee 170, Booster	4.49	0.125	5.8	0	1.1	0.3	0.96	0.7	0.3	0.100	0.03	0.07	1.25	1.92
Aerobee 170, Sustainer					2.2	0.6	1.15	0.5		0.105		0.0625		
Aerobee 350, Booster	4.49	0.125	5.8	0	1.1	0.3	0.96	0.7	0.3	0.100	0.03	0.07	1.25	1.92
Aerobee 350, Sustainer					1.1	0.6	0.57	0.6		0.100		0.035		
Astrobee 1500, Recruits only	4.49	0.125	5.4	0	1.1/ Recruit	0.9/ Recruit	0	0.7	0.3	0.100	0.03	0.07/ Recruit	1.25	1.92
Astrobee 1500, Junior only					1.1	0.9	0					0.07		
Astrobee 1500, Second Stage				1.0	1.1	0.9	0	0.7		NA		0.07		

* M = total mass, slugs
K_r = roll radius of gyration, ft
K_p = pitch radius of gyration, ft

** Propellant weight loaded error arises from tank cap'y and prop. density variations.
Inert weight errors incl. structural weight and insulation weight errors.
Propellant weight change errors arise from sliverage and off nominal mixture ratio.

TABLE II

SUMMARY OF 1σ PERTURBATIONS

(Figure Shown = Tota RSS of Components)

						SUSTAINER							BOOSTER						
Date	Author	Report	Ball. Wind (ft/sec.)	Tower Align. (deg.)	Tip-off *	Thrust Align. (deg.)	Fin Align. (deg.)	Drag (%)	Propellant Weight (lb)	Inert Weight (lb)	Thrust Level (%)	Coast Time (sec)	Thrust Align. (deg.)	Fin Align. (deg.)	Drag (%)	Propellant Weight (lb) **	Impulse (lb/sec) **	Thrust Level (%)	Inert Weight (lb)
										AEROBEE 150									
1/58	Thomas	1389A (Rev)	--	--	--	.0625	--	--	--	--	--	NA	.067	--	--	--	--	--	--
2/59	Thomas, Callaghan	1724	--	--	--	.0625	.02	--	--	--	--		.0625	--	--	--	--	--	--
5/66	Hatalsky, Kreuler	870 FR-3	4.5	.125	2.5° sec.	.0625	.0625	--	--	--	--		.0625	.0625	--	--	--	--	--
7/68	Dunn, Sollow	9065 FR-2	2.1	.125	0	.0625	.0625	5	3.2	1.0	--		.05	.0625	5	1/2%	--	--	5.0
7/68	" " "	" " "	3.0	.125	0	.0625	.0625	5	3.2	1.0	--		.05	.0625	5	--	--	--	5.0
6/69	Sollow	1316TR-1	4.5	.125	0	.0625	.0625	5	2.9	1.0	--		.05	.0625	--	--	1/2%	--	5.0
3/70	Sollow, Hoult	1316TR-5	4.8	.125	0	.0625	.0625	5	2.9	1.0	--	NA	.05	.0625	--	--	1/2%	--	5.0
										AEROBEE 170									
6/68	Dunn, Hatalsky	8720-04 K-1	2.1	.125	--	.0625, .0417	~~--~~ .0417	5	3.5	1.0	--	NA	.07	~~--~~ 0.033	5	--	750	--	6.0
2/70	Sollow	1316TR-4	1.5	.125	--	.0625	--	5	3.5	1.0	--	NA	.07	--	5	--	750	--	6.0
										AEROBEE 300									
9/58	Thomas	1504	1.5	--	--	.0625	.020	--	--	--	--	--	.0625	--	--	--	--	--	--
12/60	Meyers	APGC-TN-60-106	4.7	0	--	.063	.029	10	--	--	2	--	.063	--	--	--	--	--	--
										AEROBEE 350									
4/63	Sollow	265FR-4	2.1	.125	--	.035	.025	5	20.0	1.0	--	NA	.07	.05	5	2.5	--	--	6.0
11/66	Chalfant	749FR-11	2.1	.125	--	.035	.025	5	20.0	1.0	--	NA	.07	.05	5	2.5	--	--	6.0
										ASTROBEE 1500									
4/61	Kramer	1993	2.8	.167	1.0° @ SS IGN	.067	.067	6.7	0	--	1.6	0.66	.067	.067	6.6	--	--	1.6	--
11/61	Kramer	1993A	2.8	.167	" "	.067	.067	6.7	0	--	1.6	0.66	.067	.067	6.6	--	--	1.6	--
7/66	Sollow, Hatalsky	749FR-15	2.9	.25	α = .5° q = 5.78° sec	.07	.07	10.0	0	29.0	1.4	--	.07	0	10.0	--	--	1.4	--

* Units as noted
** Except as noted