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Variations in Launch Vehicle Performance From a Mission Planning Viewpoint

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Abstract

Launch vehicle performance is discussed from the user's point of view and with respect to payload determination in early phases of spacecraft design and mission planning. The emphasis is on the differences between (1) performance guaranteed for a specific, well-identified mission and (2) performance estimated on a general basis before the mission has been studied in depth by the cognizant agencies.

Checklists of requirements are presented as aids in reviewing preliminary launch vehicle weight and performance data. These can assist in determining that the factors that affect the weight of spacecraft support hardware and mission-peculiar jettison weight of the injection stage have been recognized.

Variations in Launch Vehicle Performance From a Mission Planning Viewpoint

I. Introduction

Launch vehicle performance is one of the major factors which constrains spacecraft design. In a gross sense, it affects future mission planning; in quite detailed and recognizable ways, it affects project planning of funded missions. When viewed over a period of time, performance quotations for a given vehicle reflect an appreciable noise content which, though perhaps disturbing, is historically an inherent characteristic. The major purpose of this discussion is to describe the phenomenon and categorize the sources of variation in quoted performance values. A secondary objective, however, is to provide checklists to aid in verifying that estimates of launch vehicle performance account for all factors of importance. The time history of performance variations is presented for *Mariner* Mars 1964 and for *Surveyor*. The subsequent addition of similar data from future programs is desirable, because such data would further illustrate the extent of performance variations from program go-ahead to targeting.

II. Basis for Performance Predictions

For launch vehicles in flight qualified status, guaranteed performance is derived from flight test data. The basic element of a "performance generator" is a mathematical simulation of the vehicle into which selected flight measurements are introduced. The measured data include telemetry from propellant and propulsion subsystems and metric tracking. Telemetry from the inertial guidance system is also available from *Centaur* vehicles. Wind measurements must also be made to provide a profile from which the performance increment or decrement from winds is derived.

In one sense, the computer program for flight performance simulation resembles spacecraft orbit determination programs, where certain astronomical constants can be preassigned or, alternatively, solved for. In the launch vehicle case, engine specific impulse and aerodynamic drag typify such "constants," although both are time-variable functions. Iterations are performed to determine maximum likelihood values of all the performance parameters.

A. Measured Parameters Required for Performance

Multistage launch vehicles derive their injection energy capabilities incrementally from each stage. In the case of multiple restart engines, one or more velocity increment may be obtained from a single stage. The dispersions in tracking measurements imply a corresponding uncertainty in the velocity contribution of each stage or phase of flight. This holds whether the ΔV is obtained from ground tracking or from an on-board velocity meter. The dispersion in wind measurements corrupts the derived engine performance of lower stages. In general, the derived performance of upper stages tends to be somewhat masked by the uncertainties in performance of lower stages.

A basic parameter of performance estimation is the specific impulse delivered by each engine. This parameter cannot be measured directly. It must be inferred from both the measured velocity profile, on-board measurements of propellant pressures and flow rates, and from time intervals between valve openings and closures. Thrust buildup and decay must be accounted for in the simulation. Other factors that may be involved include ice accretion, propellant boiloff, gases used in chilldown and for purging, lubricants consumed in flight, and residual fluids at cessation of the final thrust application.

B. Engine Performance

Prior to installation, each individual engine is tested on the ground to determine its performance. Because no routine ground test can fully duplicate flight conditions, a correlation must be determined such that ground measurements can be converted into expected flight performance. The computer simulation and iterative reconstruction are the key to this correlation.

As evidence of the slow convergence of this correlation process, it is interesting to note that in the fourth quarter of 1966, both Lockheed Missiles and Space Company and General Dynamics/Convair re-evaluated the statistical flight data on which their engine specifics were based. The *Agena* family had experienced about 200 flights, and the NASA *Atlas SLV-3* had over 30 launches behind it. Nevertheless, each company reduced its guaranteed performance for the *Mariner* Venus 1967 mission. Launch vehicle performance contingencies, which were expected to accrue to the benefit of the spacecraft, were absorbed by the vehicle.

C. A Statistical Problem

Accuracy of trajectory computation depends on the quality of metric (radar) tracking, which in turn, is affected by launch azimuth and varies according to whether the flight is direct ascent or parking orbit. For example, second burn of an injection stage may occur with ship coverage only. Even with excellent ground station coverage, as reported in *Surveyor V* mission reports, significant gaps occurred in tracking data actually acquired. Winds aloft and pitch programs also affect the flight profile and vehicle performance. Thus, the limited number of launches of a given type vehicle, coupled with wide variations in ground tracking coverage, are factors which influence the quantity and quality of the data upon which guaranteed performance is generated from the mathematical reconstruction of each flight.

For a given vehicle, measured performance data are available from whatever missions are flown and thus, performance for a spectrum of *vis viva* energies can only be extrapolated or interpolated, using a flight simulation program. Only by allocating appropriate contingencies, therefore, can the gap between desired, statistically significant data and the flight data actually available be closed.

Because launches cannot be made for the purpose of developing performance statistics, it is reasonable to expect changes in quoted performance as the body of statistical data grows. Superimposed on this is a tendency for mean values to shift as new vehicles are tuned, or as performance improvements are incorporated in older vehicles.

III. Contingencies

In view of the previous discussion, it is clear that allowance must be made for contingencies, especially where adequate statistical data is lacking or where wide variances are anticipated in subsystem performance.

A. Structural Weight

Large propellant tanks are universally fabricated from rolled sheet or plate. Thickness tolerances are imposed by the vehicle manufacturer and some sheets are occasionally hand selected to minimize vehicle weight. As a consequence of tolerances on structural materials, no two tanks have identical masses. Nominal weights are established for performance prediction, but targeting for a mission is not initiated until a vehicle stage has been fabricated and weighted to determine its actual or "tag" weight.

B. Propellants, Gases, and Coolants

Lower stages of launch vehicles invariably employ bipropellant propulsion systems because of the higher efficiency. This introduces the problem of deriving the mixture ratio attained throughout the duration of engine burns. It is interesting to note that the *Saturn V* has a programmed shift in mixture ratio at the point in the ascent trajectory where optimum overall performance dictates a change from maximum thrust to maximum specific impulse. As is generally true, maximum power and maximum efficiency do not occur at the same operating point.

Propellant reserves are needed to insure that, under adverse variations in mixture control, adequate quantities of propellants would be available to cope with the expected variations in aerodynamic forces on the vehicle and in engine specific impulse. A related consideration is propellant bias, which is an additional quantity of fuel provided to insure that, under the conditions of soft shutdown, the oxidizer is depleted first. Propellant contingencies are sometimes provided in addition to propellant reserves.

Attitude control gases are required in quantities that vary with the mission. A long coast phase in parking orbit would require more gas than a direct ascent injection. Because gas consumption cannot be precisely predicted, enough reserves are carried to insure that vehicle control will be available under 3-σ adverse conditions, or worse.

Telemetry transmitters and guidance packages require cooling in flight. In some transmitters, beryllium heat sinks are selected as to size in accordance with the time from launch to the end of desired data transmission. In other vehicles, subliming coolants are used. In either case, the weight is traded one for one with payload.

When retro, posigrade, and/or spacecraft orientation maneuvers are required of the injection stage, contingencies are allowed both for impulse propellants and for attitude control gases. As for coolant requirements, the weights are a function of the mission.

Post-flight analyses to determine vehicle performance require that residual propellants and gases be determined for their contribution to jettison weight. The difficulty in direct measurement of residuals is apparent.

C. Drag

Nose fairings are a factor in aerodynamic drag and in the degree of thrust vector control required. Pressure fluctuations around the fairing (buffeting) and gusts couple with vehicle dynamics to determine engine gimbal angle variations and consequent variations in propulsive efficiency. Brushing of Thermolag coatings on a nose fairing creates variable roughness and corresponding drag changes.

Base drag is also a source of uncertainty. Separation of the various drag components from the total drag is required for proper simulation and hence performance prediction. Yet only thrust-minus-drag can be extracted directly from tracking measurements. The important factor in aerodynamic drag is the integrated effect over the wide range of flight Mach numbers. The drag contingency currently carried for *Surveyor* (after 15 launches) and for *Mariner* Mars 1969 is 30 lb of equivalent payload. New shrouds could require larger contingencies.

D. Changes in Requirements

Contingencies should be allowed for possible changes in launch vehicle jettison weight due to refinements in mission requirements that determine spacecraft support weight. Hardware items which could be involved include:

(1) Spacecraft adapter.

(2) Spacecraft separation system.

(3) Spacecraft destruct system (if required).

(4) Spacecraft environmental instrumentation, including sensors, harnesses, amplifiers, and signal conditioners.

(5) Spacecraft separation rate monitors (if required).

(6) Umbilical and/or separation connectors and harnesses.

(7) Relays or firing units for pyrotechnic devices.

(8) Nose fairing extensions (if appropriate).

(9) Spacecraft fuel leakage detection system.

(10) Science instrument checkout stimuli.

Another area for consideration is requirements that change launch vehicle weight, but in ways which disqualify as "spacecraft support weight." The trend is for the launch vehicle contractor to offer optional and mission-peculiar kits, which allow peculiarization of the vehicle at lower cost and higher reliability. Examples are:

(1) Retro or posigrade maneuver kits.

(2) Telemetry kits of different power and different heat dissipation capabilities.

(3) Provision for modular addition of telemetry channel capacity.

(4) Sun sensor eyeball kit (*Agena* only).

(5) Optional attitude control bottle size or number.

(6) Vehicle destruct kits.

(7) Modularized stage zero solid rocket motors (*Titan*).

(8) Multiple restart engine kit.

(9) Auxiliary timers.

(10) Batteries of various watt-hour ratings.

IV. Mission-Peculiar Performance

A. Mission Study Phase

Unless specifically requested and negotiated, mission-peculiar performance is not normally provided by a contractor or NASA launch vehicle agency. The data most commonly provided are for on-going programs with only nominal recognition, if any, of the requirements of the proposed mission. During advanced mission studies, the requesting agency must adjust the payload weight to account for differences in spacecraft support weight, optional and mission-peculiar kit weights, launch azimuth velocity losses, parking orbit altitude, and other factors.

When several sources of current performance data for a given vehicle are available, the disparity is usually less than it appears. When these data are reduced to a common set of ground rules, an acceptably small discrepancy usually results. Errors in bookkeeping are less prevalent than inadequate definition of the ground rules, which are necessary to properly qualify a given set of performance data. The depth and scope of the particular mission study at hand determines the extent to which the allowable payload weight should be refined.

Not the least of these considerations is the matter of contingencies. It would be unrealistic to predicate a mission study on launch vehicle performance data that does not allow for proper contingencies. At the time cognizant agencies make guaranteed performance available, it will include contingencies. This was true when good engineering judgement was the primary criterion for determining reserves and contingencies. However, incentive launch contracts now inject considerations of financial risks directly into the process of determining guaranteed performance.

B. Funded Mission Phase

Launch vehicle performance continually changes as the user periodically samples the sources which generate it. Figure 1 shows the variation in committed capability of the *Atlas LV-3A/Agena D* from February 1963 to November 1964. Activity by launch vehicle agencies was funded during this period, and the mission was clearly defined.

A rise in capability of the second vehicle (Fig. 1) scheduled for launch is shown in November 1964. This increase was not due to distribution of contingencies, but because of special measures taken to obtain an emergency extension to the launch period. If a similar plot were available for *Mariner* Venus 1967, it would show less variance and no increase at the time tag values became available and targeting began.

Figure 2 is a similar plot for the *Atlas LV-3C/Centaur* launch vehicle during the *Surveyor* mission phase from January 1961 through May 30, 1966, the date of the first *Surveyor* launch. The payload capability shown is for direct ascent to injection. The payload performance for each of the seven *Surveyor* missions is tabulated in Technical Report 32-1265, along with a description of the factors which contributed to a total payload gain of about 600 lb. This occurred over the period from March 1963 to the final launch in January 1968. Of the 600 lb, approximately 200 lb resulted from introducing the *SLV-3C*, when used in the parking orbit ascent mode.

C. Standardization

The high cost of tailoring launch vehicles to fit the requirements of individual missions and spacecraft set off a strong trend toward standardization, as discussed in Section III-D. The *Atlas SLV-3A* and *SLV-3C* are current examples. Each of these vehicles has higher performance than the *LV-3A* and *LV-3C*, respectively. The standard vehicles, however, are designed to satisfy flight structural and heating loads that represent the envelope of the maximum loads arising from all the types of missions considered in vehicle design. Thus, for any single mission, the launch vehicle has more structural weight than

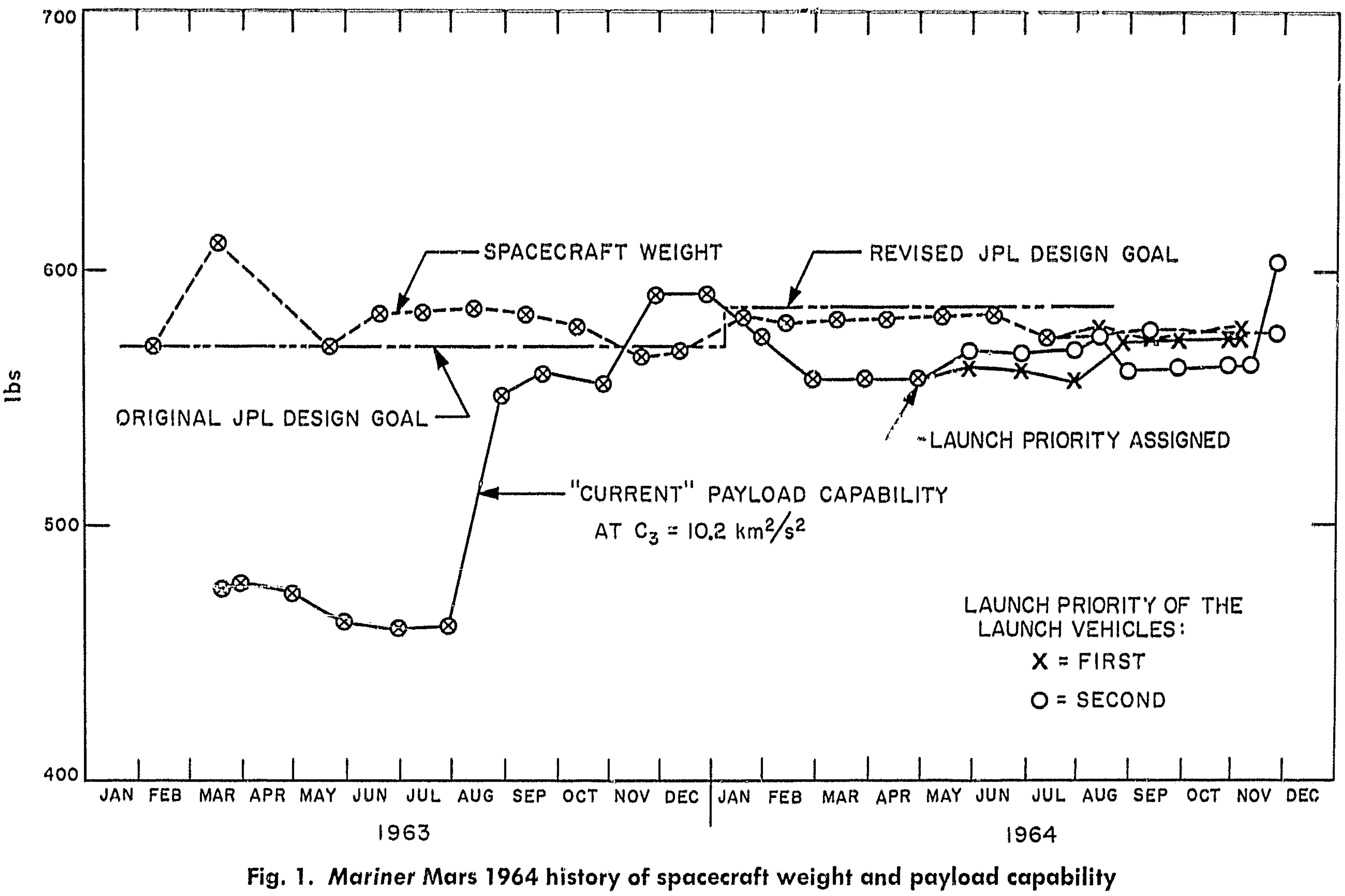

Fig. 1. ***Mariner*** **Mars 1964 history of spacecraft weight and payload capability**

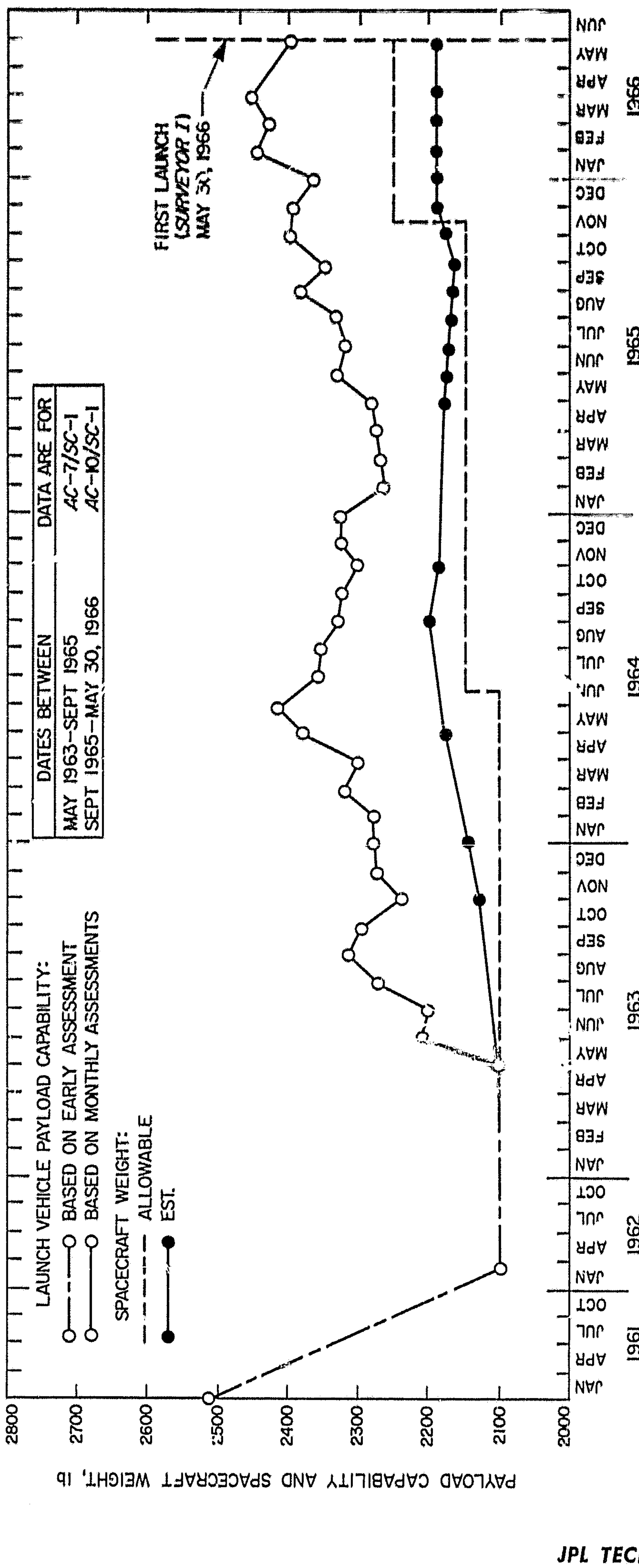

Fig. 2. *Atlas LV-3C/Centaur payload capability history for Surveyor I (direct ascent)*

the minimum required for the mission. In this sense, the use of standard launch vehicles trades peak performance capability for lower cost.

A similar situation will exist when modular height nose fairings become available, as planned for the *Titan* vehicles. The vehicle must support the largest fairing, and will consequently have excess strength for shorter fairings. In particular, the vehicle must survive the most severe buffet loads imposed by the most buffet-prone fairing, and hence have excess margins of safety for the less critical fairings.

This trading of peak performance for lower cost is not of concern when the launch vehicle performance capability comfortably exceeds that required. When the predicted performance margin is negative, however, the questions that arise are:

(1) What launch constraints can be relaxed to improve performance?

(2) What secondary functions provided by the launch vehicle can be reduced or eliminated to reduce weight?

(3) How much excess structural weight exists in the launch vehicle? Where is it located? How much of it can be extracted economically; e.g., by deeper milling or by using thinner skins?

As evident, trade-offs, which require mutual resolution by the spacecraft and launch vehicle, exist. The performance trade-offs, however, are really a part of the larger task of mission design and optimization.

V. Conclusions

Conclusions reached concerning launch vehicle performance are:

(1) In the short term, changes in the quoted value of performance of a given launch vehicle occur on a continuing basis. These changes are mostly due to differing ground rules.

(2) Changes in performance over a longer term are usually the result of tuning the vehicle, better statistics, and hardware improvements. Better statistics can result in performance decreases, whereas the other two causes almost always increase the performance.

(3) Meaningful performance data require a surprisingly large set of ground rules to qualify the data properly. The greater the accuracy of performance data, the higher is the degree of detail required to describe the vehicle. This trend becomes particularly critical when spacecraft weight is close to the limit of the capability of the launch vehicle.

(4) Trends toward standardization of launch vehicles have and will continue to trade peak performance for lower cost.

(5) Determination of propellant reserves and propellant contingencies is not based simply on the average (RSS) of the hardware and trajectory uncertainties, but includes consideration of the risks acceptable to the launch vehicle system manager.