MARINER MARS 1964 ACOUSTICALLY INDUCED VIBRATION ENVIRONMENT*

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This paper discusses some work performed at the Jet Propulsion Laboratory for enhancing the probability of survival of Mariner Mars 1964 in the acoustically induced vibration environment associated with the boost phase of the mission.

Following a brief technical description of the spacecraft, a discussion is given of the philosophy used in defining the vibration qualification and acceptance criteria.

Two techniques used to estimate the lift-off and transonic vibration spectra for particular locations on the spacecraft and on the spacecraft adaptor are shown in detail: (a) a method of measured acoustic acceptances, and (b) an empirical method suggested by Dr. P. Franken of Bolt, Beranek and Newman, Inc. Some of the Mariner ground test activities (vibration, acoustic, wind-tunnel), pertinent to the extraction of parameters for use in the predicting techniques, are also given.

The predictions and the flight data are compared. Deviations in the estimating parameters and their effects on the prediction, based on the flight measurements, are indicated.

The adequacy and conservatism of the test requirements are shown by the spectra ratios of the behavior of the adaptor during ground tests to the corresponding maximum recorded levels during flight.

Finally, a procedure for defining test requirements for future programs is recommended, along with suggestions for study in related areas.

INTRODUCTION

On November 28, 1964, with the launching of the Mariner IV spacecraft on its 8-1/2 month voyage to the vicinity of Mars, the United States began one of the most difficult missions in its program of unmanned space exploration.

This discussion relates some of the work performed at the Jet Propulsion Laboratory (JPL), under contract to the National Aeronautics and Space Administration (NASA), for assuring the integrity of the Mariner spacecraft in the acoustically induced vibration environment associated with the launch phase of the mission.

Emphasis is placed upon the approach taken in predicting the lift-off and transonic vibration response spectra for the spacecraft bus and adaptor several months prior to flight. These predictions were based principally on Mariner vehicle simulated acoustic and vibration laboratory test data, and on related data obtained from similar programs such as Mercury/Atlas and Ranger.

Mariner Technical Description

The Mariner-Mars 1964 Project was directed by the Office of Space Science and

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Applications of the National Aeronautics and Space Administration. Project management was assigned to the Jet Propulsion Laboratory, Pasadena, California, operated by the California Institute of Technology. NASA's Lewis Research Center, Cleveland, Ohio, was responsible for the launch vehicle; Goddard Space Flight Center supervised the launch operations. Tracking and communication with the Mariner was accomplished under the auspices of the NASA/JPL Deep Space Network (DSN). Instruments for scientific investigations performed by Mariner were provided by scientists representing eight universities and two NASA laboratories.

The Atlas, designed and constructed by General Dynamics/Astronautics, was purchased through the Space Systems Division of the U.S. Air Force System Command, and Rocketdyne Division of North American Aviation, Inc., built the propulsion system. Radio command guidance was by Defense Division of General Electric Co., and the ground guidance computer by the Burroughs Corp. The Agena D stage and its mission modifications were purchased directly by LeRC from Lockheed Missiles & Space Co. Bell Aerosystems Co., provided the Agena propulsion system. In addition, some 61 key subcontractors to JPL provided components, assemblies, hardware and personnel for the Mariner-Mars 1964.

Overall mission objectives were to provide experience in the operation of long-duration flights, and to perform scientific measurements between the orbits of Earth and Mars, and near Mars.

The mission was unprecedented:

1. The distance to Mars is some 350 million miles, compared with 180 million miles for the 1962 Mariner II Venus fly-by.

2. The Mars flight time is about 8-1/2 months, compared with 3-1/2 months for Mariner II.

3. A communications distance of 150 million miles compares with the record 53.9 million miles established 20 days after Mariner II flew past Venus.

4. Some 138,000 components on the Mariner were required to function in excess of 6,500 hours in space.

5. Extreme demands were placed on the accuracy and performance of the Atlas/Agena D launch vehicle.

Due to the mission's difficulty, many new engineering applications were required, including the use of an improved propellant system for the Agena D, a new radio system, the first use of the star Canopus for attitude reference, and a midcourse motor capable of firing twice.

Physically, Mariner weighs 575 lb, including about 60 lb of scientific instruments. Because the spacecraft travels away from the Sun, it uses four solar panels instead of the two carried by Mariner II. The Mariner basic structure is an octagonally shaped magnesium framework with eight compartments (Fig. 1). These eight compartments, composed of a myriad of possibly vibration and acoustically sensitive components, house the following: (a) Bay 1, power supply and synchronizer, battery charger, and squib firing assembly, (b) Bay 2, midcourse maneuver rocket engine, (c) Bay 3, science equipment and Data Automation System, (d) Bay 4, data encoder and command subsystems, (e) Bays 5 and 6, radio receiver, transmitters and tape recorder, (f) Bay 7, Central Computer and Sequencer and attitude control subsystem, (g) Bay 8, power booster regulator and spacecraft battery. All compartments provide structural support for the spacecraft.

Six of the electronics compartments are temperature controlled by light-weight, fragile louver assemblies on the outer surfaces. The octagon's interior is insulated by multi-layer aluminized mylar thermal shields at the top and bottom of the structure.

The four solar panels, each 71-1/2-in. long and 35-1/2-in. wide, are attached to the sunward side of the octagon. Solar pressure vanes which act as an auxiliary attitude control system are located at the ends of the panels. Each panel, fabricated from extremely light-weight aluminum sheet, weighs 18.7 lb, including solar cells. Panel construction is 0.0035 in. aluminum sheet formed into a corrugation that is bonded to the 0.003 in. cell-mounting surface. During the development of Mariner, it became apparent that the solar panel structural weight fraction would be an unbearable percentage of the total system weight, if the more conventional Mariner II and Ranger panel configuration and construction were used. As a result, an unconventional "damped" strut system was developed to support the panels while in the boost configuration. While this development resulted in the fragile structural configuration, it provided a significant reduction in weight.

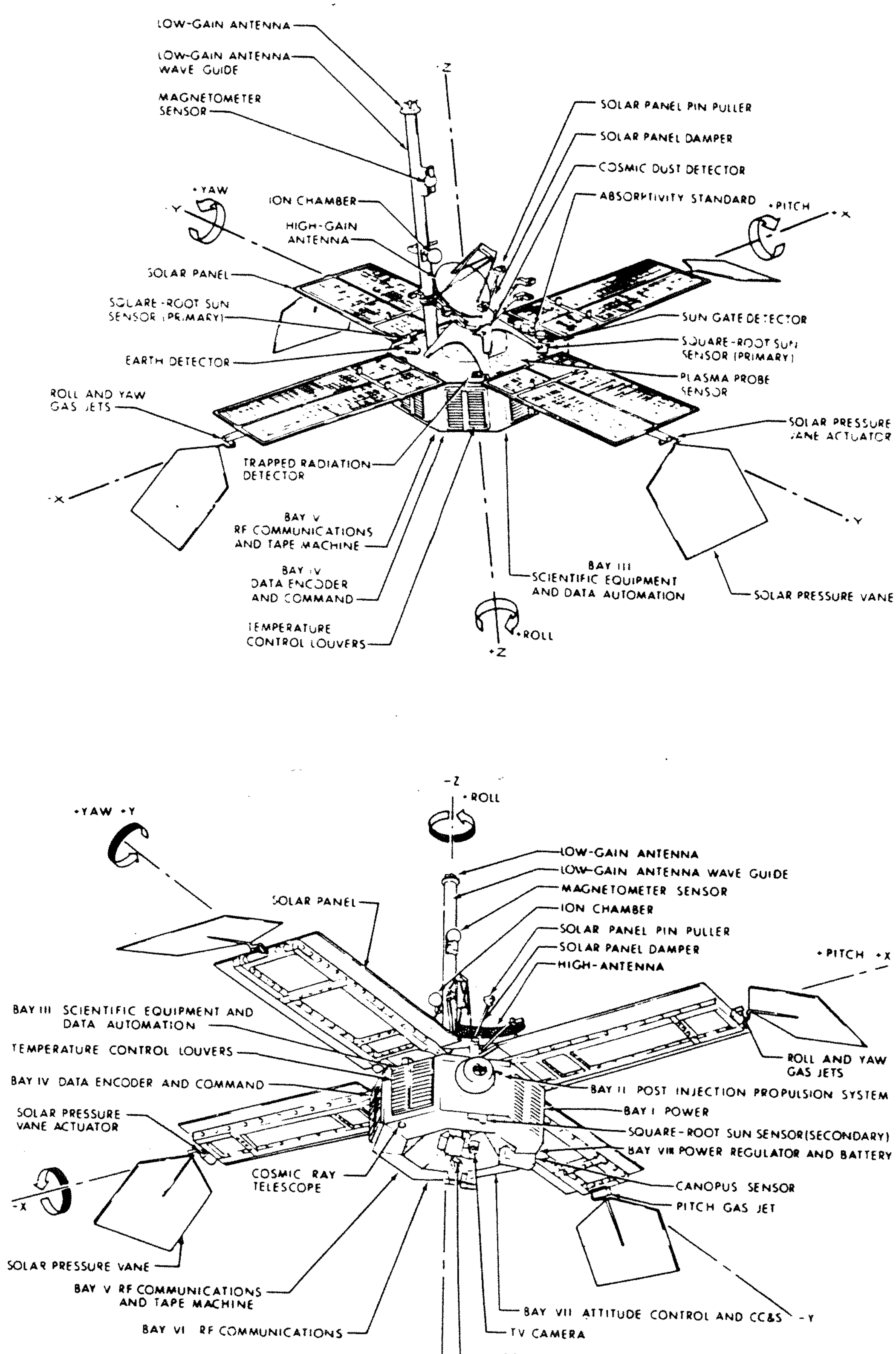

Fig. 1. Mariner-Mars 1964 spacecraft

The interior of the octagon contains gas bottles and regulators for Mariner's dual attitude control gas system. The propellant tank for the liquid-fuel rocket engine is supported by a cantilever arrangement inside the octagonal cavity, with the nozzle protruding through one of the eight sides of the spacecraft.

Two sets of attitude control jets, consisting of six jets each, control the spacecraft in three axes. The jets are mounted on the ends of the solar panels near the pressure vane actuators.

The high-gain antenna is attached to the spacecraft by an eight-legged superstructure atop the octagon. Its fragile honeycomb dish reflector is an ellipse, parabolic in cross-section, 46 x 21 in. The antenna, which weighs only 4-1/2 lb, is in a fixed position, so that it will be pointed toward the Earth during the latter portion of the Mariner flight, including the planet encounter and postencounter phases.

The low-gain omni-antenna is mounted on the end of a circular aluminum tube, 3.88 in. in diameter and extending 88 in. from the top of the octagonal structure. The tube, a heavily damped structure, similar to the solar panels, acts as a waveguide.

The Canopus star tracker assembly is located in the shade of the spacecraft, on the lower ring structure of the octagon, for a clear field of view. Sun sensors are located on both the top and bottom surfaces of the spacecraft bus to provide spherical coverage.

Mariner carries seven interplanetary and planetary science instruments. One experiment, occultation, requires only the spacecraft communications system. The ion chamber and helium vapor magnetometer are mounted on the low-gain antenna support boom above the spacecraft. The trapped radiation detector and plasma probe are attached to the upper octagonal ring. The cosmic ray telescope looks through the lower ring of the octagon from one of the compartments. The cosmic dust detector is attached to the superstructure. The television camera and two planetary sensors are mounted on a scan platform below, and in the center of the octagon.

The launch vehicle employed for the orbital injection of Mariner was the Atlas/Agena D. Mariner-Mars 1964 was the first NASA space mission to require a two-burn capability in the improved Agena D. An increase in payload capability of about 80 lb was also gained over the standard Agena by the use of lighter weight components and an improved propellant utilization system.

Atlas ignition and lift-off, with its attendant vibration/acoustic environment, is the first of the critical dynamic environments discussed in this paper. As the vehicle rises through the atmosphere, it passes through the transonic velocity region, becoming exposed to the second critical environment of interest. There are, of course, other regions of the boost phase which produce critical vibration and shock environments. Such events as engine shut-down and staging transients produce significant dynamic loadings, but are beyond the scope of this paper.

The Philosophy

Implementation of rigorous analytical techniques in the design of complex spacecraft systems is normally applied only to the definition of the basic structure. The practice of precisely calculating normal modes and structural response, and performing detail stress analyses based on these calculations, is a reasonably common activity throughout the industry, although this effort is nominally constrained to the lower range of frequencies in the vibration spectrum. However, this approach is not practiced for the so-called "environmental" vibration aspects of the dynamics problem, principally due to the fact that (a) the analysis of complex electronic systems for their normal modes is not within the state-of-the-art, and (b) there exists only limited information on the "fragility" of electronic equipment. To ensure environmental adequacy for these kinds of systems, the approach has been: (a) design the system based on its functional and operational requirements, using empirically proven packaging techniques and various "rules of thumb," and (b) qualify to a set of requirements established by a general specification.

The principal problem associated with this technique, however, is the task of assessing the projected system and prescribing the contents of the specification at a time in the program's development when little is known about the configuration, launch vehicle, subsystem interactions, etc.

This, essentially, was the approach employed on Mariner. Since Mars opportunities occur only once in 25 months, necessitating a tight, definitive schedule, the issuance of the specifications at a very preliminary stage in the development forced a conservative set of requirements. To meet the needs of the Mariner mission, a set of test requirements was defined. Then, as development progressed and information peculiar to Mariner was obtained, these initial requirements were continuously reviewed to ensure their appropriateness.

Specifically, the Mariner Flight Acceptance spectra were established by generously enveloping the 95th percentile level (in 50 cps bands) from inflight vibration data taken from Rangers 1 through 5. Consistent with the JPL policy of setting the Type Approval test requirements at more severe levels than the Flight Acceptance, for vehicle qualification, the 95th percentile spectra were increased 4.5 db. After some study of the wideband vibration time history of a number of "hammerheaded" launch vehicles, the test time duration was rather arbitrarily established at 1 minute for Flight Acceptance and 3 minutes for Type Approval. It appeared that this duration would adequately cover the period of time during flight that the wideband level would be within 10 db of the maximum (Fig. 2).

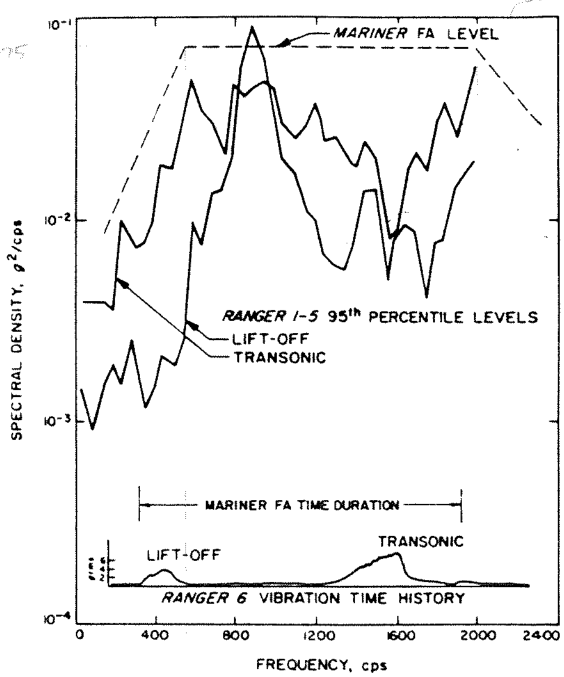

Fig. 2. Ranger wideband vibration time history and 95th percentile flight data compared to Mariner flight acceptance test requirements

Since Ranger was considered to be of sufficiently similar general configuration to extrapolate its data to Mariner with some confidence, and since the Type Approval margin was felt to be well in excess of the Ranger 99 percentile value, these initial requirements were considered generally conservative, and our experience indicated that there should be at least one peak in the power density spectrum during flight within 3 db of the maximum level. It is noted that these initial requirements were never changed during the course of the program.

The Ground Test Program

It has been generally established that the fully integrated system configuration provides the only true mechanical, electrical, and thermal environment for the various spacecraft elements. Due to the state-of-the-art in estimating the effects of the many inputs to a highly complex system such as Mariner, there exists an unavoidable requirement for a comprehensive ground test program early in development. The following sections describe some of the Mariner ground test activities pertinent to the estimation of the flight environment.

Vibration Testing — To simulate the deleterious effects of the vibration and acoustic environment which accompanies Atlas/Agena operations from launch to injection, the Mariner Proof Test Model spacecraft was subjected to both swept-sinusoidal and band-limited random vibration along the longitudinal axis, selected lateral axes, and torsionally (1).

The purpose of the Proof Test Model tests, that of demonstrating design adequacy of the vehicle in its most representative configuration, was achieved by evaluating the expected environment and then prescribing tests that were a practical compromise between realism and economy. These Qualification Tests were intended to qualify the design and to demonstrate, with a margin, a minimum level of equipment capability. To compensate for the statistic limitations of the small sample size, and to provide assurance in the location of faults and inadequacies, the imposed test conditions were, by selection, more severe than both the flight acceptance test requirements and the operational conditions.

All flight model spacecraft were subjected to three axes of random vibration (Fig. 3), which, while comparable to the expected 95th percentile environment in severity, were intended to be mild enough to avoid fatigue or a reduced life expectancy of the vehicle, yet severe enough to indicate workmanship defects and subsystem early life failures.

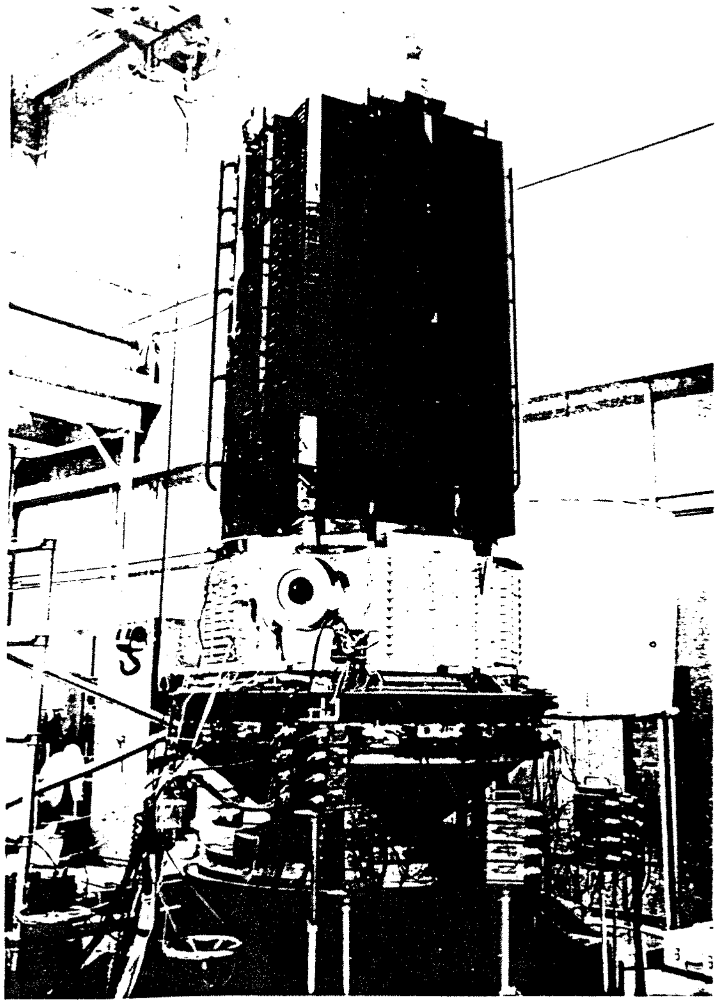

Fig. 3. Mariner IV subjected to roll axis vibration testing

To develop the proper dynamic characteristics of the flight spacecraft, but in order to avoid an explosively hazardous condition, the PTM Post Injection Propulsion System (PIPS) was installed in place of the flight unit. Its fuel tank was filled with 21.5 lb of distilled water and pressurized to 150 psi; its nitrogen tank was unpressurized.

Figure 4 represents the spectra ratio of the spacecraft bus response to that of the spacecraft adapter, obtained from longitudinal axis vibration testing, and used in the prediction of the bus flight vibration. It is noted that this is not considered a transfer function in the true sense, for the following reasons:

1. It does not account for the acoustic acceptance of the structure.

2. It is a measure of the response of the structure to a single axis separation plane vibration input.

3. Phase information is lacking.

Scale Model Wind-Tunnel Testing — A series of wind-tunnel tests were performed on a one-tenth scale model of the Agena vehicle with the Mariner shroud at the 8- x 6-ft transonic tunnel of the NASA-Lewis Research Center (Fig. 5). The primary test objectives were to define and measure:

1. The locations and magnitudes of pressure fluctuations due to shock wave oscillations and flow separation.

2. The longitudinal and radial correlations of the pressure fluctuations.

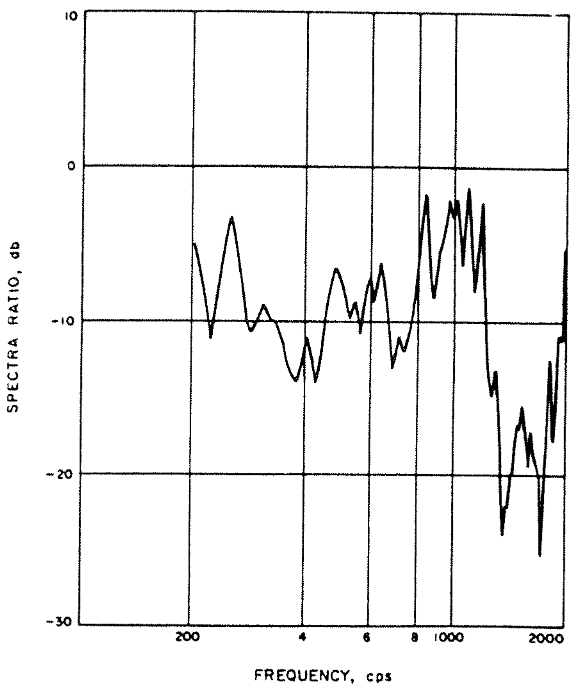

Fig. 4. Ratio of vibration response of spacecraft bus to adaptor (roll axis input)

3. The frequency distributions of the pressure fluctuations.

4. The static pressure distributions.

On the basis of test results reported in the literature for "hammerhead" vehicles of similar configuration, it was expected that the maximum flow disturbances would occur in the high subsonic region (2,3). Accordingly, test runs were made at incremental Mach numbers from 0.55 through 2.0 at various angles of attack. Two roll orientations were included to aid in assessing the interference problems within the rectangular wind-tunnel test section.

Application of model data to a full-scale vehicle requires the consideration of certain scaling laws. The scaling relationships which apply here are discussed in Ref. (4). When both fluctuating pressure coefficient and Strouhal number are assumed independent of vehicle scale, the resulting nondimensional scaling relationships are:

$$\left(\frac{\Delta P}{q}\right)_{fs} = \left(\frac{\Delta P}{q}\right)_{ms}, \tag{1}$$

$$\left(\frac{\omega \times D}{V}\right)_{fs} \quad \left(\frac{\omega \times D}{V}\right)_{ms} \tag{2}$$

and

$$\left(\frac{P(\omega) \times V}{q^2 \times D}\right)_{fs} = \left(\frac{P(\omega) \times V}{q^2 \times D}\right)_{ms}, \tag{3}$$

where

$P(\omega)$ = power spectral density, $(\Delta P)^2$/cps,

q = dynamic pressure, lb/ft^2,

P = root-mean-square pressure fluctuation, lb/ft^2,

ω = circular frequency, sec^{-1},

V = velocity, ft/sec,

D = vehicle diameter, ft,

fs = full scale, and

ms = model scale.

Equation (2) illustrates the inverse proportionality of fluctuating pressure frequency on vehicle scale. The nature of this effect was considered in the design of the instrumentation system, resulting in the use of a system with very high-frequency capability. The pressure sensors on the model were piezoelectric crystal microphones, linear to beyond 16,000 cps.

Preliminary data analysis was performed by Lockheed Missiles and Space Company under contract to NASA (5). At the time of preparation of this paper, the model wind tunnel data were still under analysis. Since there is concern over the tunnel calibration techniques and the background noise level, at this writing there exists some reservations regarding the validity of these data.

At the test Mach number of 0.775, the full scale sound pressure level of 150.5 db (re 2×10^{-4} μbar) was computed for a bandwidth of from 178 to 1410 cps using Eqs. (3) and (4). This wideband acoustic data was converted to standard 1/3 octave frequency bands in Table 1, using the following relationship:

$$SPL_{1/3} = SPL_{wb} - 10 \log_{10} \left[\frac{f_{wb}}{f_{1/3}}\right]. \tag{4}$$

Acoustic Testing — The Mariner acoustic test program was designed to meet the following objectives:

1. Measure the acoustic acceptances and responses of the spacecraft in the launch

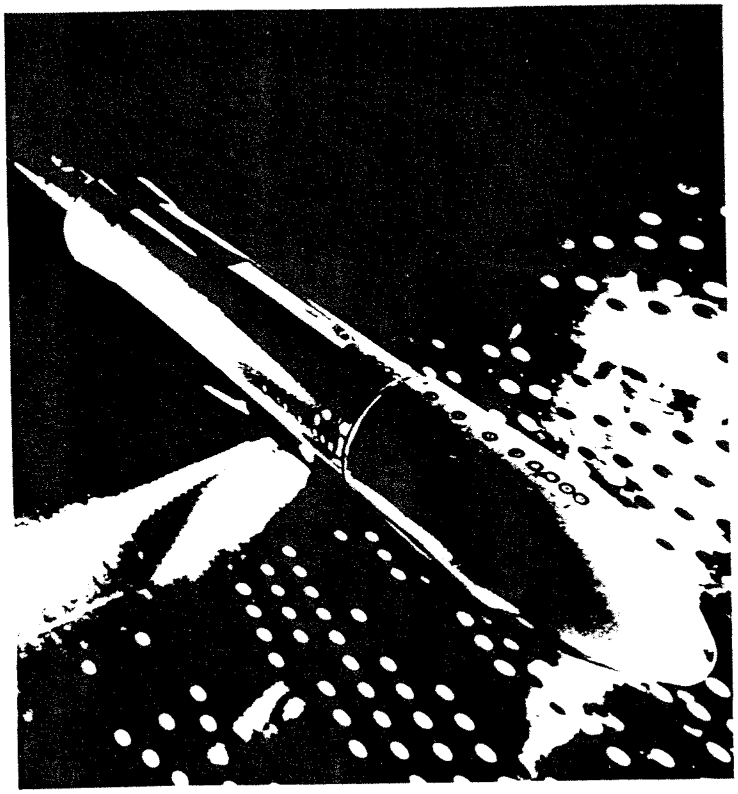

Fig. 5. One-tenth scale Mariner shroud/Agena D in NASA LeRC 8 x 6 transonic wind tunnel

TABLE 1
Calculation of 1/3 Octave Band Transonic SPL (db)

①	②	③	④	⑤
Band Center Frequency (cps)	$\Delta f_{1/3}$ (cps)	$[1232/\Delta f_{1/3}]$	$10 \log_{10} (1232/\Delta f_{1/3})$	$SPL_{1/3}$ = 150.5 - ④
200	46	26.8	14.3	136.2
400	92	13.4	11.3	139.2
630	146	8.4	9.3	141.2
800	183	6.7	8.3	142.2
1000	230	5.4	7.3	143.2
1250	290	4.3	6.2	144.2

configuration, to provide data for developing refined environmental estimates.

2. Provide equipment response data for design at an early stage of the program.

3. Insure that the spacecraft system would survive exposure to the flight acoustic environment (1).

In the first objective the measurements judged most necessary to the estimation and evaluation of the acoustically induced flight vibration were the shroud transmission loss spectra and the acoustic acceptance of the spacecraft bus and its adaptor. Preliminary reverberation chamber testing demonstrated that significant equipment responses to the expected environment would occur, due to transmission by the adaptor. The air-link constituted a negligible path for exciting the spacecraft.

A Structural Test Model spacecraft and adaptor were thoroughly instrumented with accelerometers and microphones. The assembly was encapsulated in a flight configuration shroud and mated to an Agena forward section (Fig. 6). External microphones were provided around and adjacent to the adaptor and shroud. The assembly was subjected to a wideband, high-level acoustic input, directed normal to the longitudinal missile axis (Fig. 7).

The shroud acoustic transmission loss spectra (Fig. 8) were computed by ratioing the averages of the internal and external frontal microphone recordings. The spacecraft adaptor

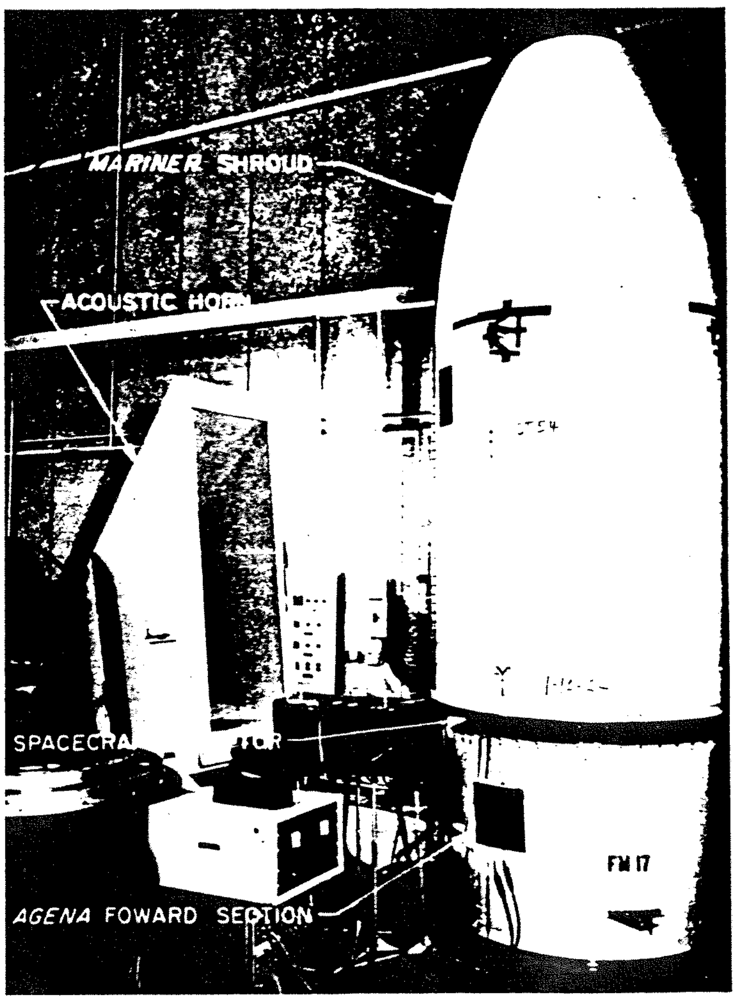

Fig. 6. Configuration of the Mariner shroud/STM during acoustic acceptance testing

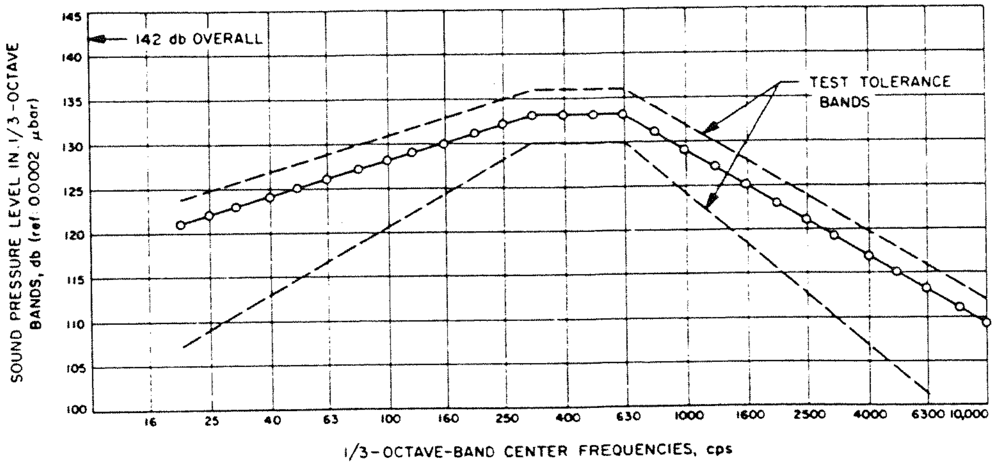

Fig. 7. Mariner PTM acoustic test spectra

acoustic acceptance spectra were computed by ratioing the averages of the adaptor vibration and external microphone recordings.

The second objective was met by prescribing a uniformly severe test on all equipment at the assembly level. Observed anomalies were formally documented, each receiving prompt corrective action.

The third program objective was achieved by exposing the Proof Test Model, without degradation, to a level in excess of the expected internal shroud acoustic level (1).

Other Available Information

The lift-off acoustic environment appeared to be dependent upon the general launch vehicle/launch pad configuration, but seemed independent of details such as payload shroud aerodynamic shape, a factor which is of prime importance at transonic speeds. Accordingly, the Atlas/Mercury launch pad measurements (Fig. 9), reported in NASA TND-1502, Ref. (6), were selected for use in the Mariner estimates, inasmuch as both vehicles are similarly configured. These data agree reasonably well with the Ranger VI launch tower measurement.

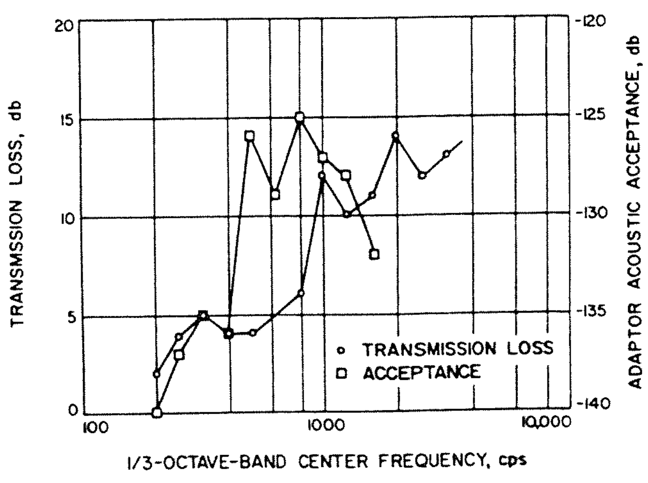

Fig. 8. Laboratory measured spacecraft/adaptor acoustic acceptance and shroud acoustic transmission loss spectra

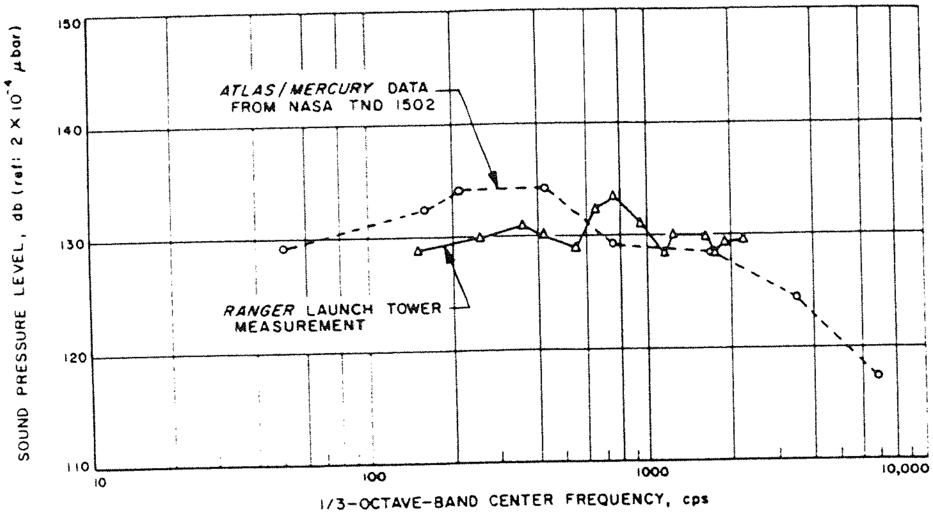

Fig. 9. Atlas/Mercury and Ranger VI (6 ft off) measured launch acoustic spectra

VIBRATION PREDICTIONS

In general, the vibration test requirements are based on conservative estimates of the expected environment. Inflight vibration data are required to refine these estimates, and to provide a basis for the development of techniques to predict the environment for similar launch vehicle systems.

The initial test requirements for Mariner were formulated at a time when few directly applicable data were available. The spacecraft design was a totally new concept; the Agena D and payload shroud, a fibreglass-honeycomb structure, were in early stages of development. The only source of applicable dynamic data available to Mariner was from the highly successful Ranger program (7).

As the spacecraft developmental program progressed, additional information (previously discussed) peculiar to the Mariner system was acquired. On the basis of this information, a second generation of Mariner predictions was performed. Specifically, the maximum vibration for the spacecraft bus and adaptor were predicted for lift-off and transonic, using the following techniques:

Acoustic Acceptance Method

The method of acoustic acceptance assumes a linearly responsive adaptor structure, for which the vibrational response spectra may be expressed by

$$20 \log_{10} g = H(f) + SPL(f)\,, \tag{5}$$

where

$H(f)$ = structural acoustic acceptance, mechanical vibration (db re 1 g), minus acoustic sound pressure level (db re 2×10^{-4} μbar), and

SPL = external acoustic sound pressure level adjacent to the adaptor (db re 2×10^{-4} μbar).

Calculations for the average lift-off and transonic vibration spectra for the spacecraft adaptor, using the method of acoustic acceptances, are shown in Tables 2 and 3.

Franken's Method

P. Franken, of Bolt, Beranek and Newman, Inc., has suggested (8) that the acoustically induced vibrational response of a cylindrical vehicle may be expressed by

$$20 \log_{10} g = SPL(f) - 20 \log_{10} w + TF(f)\,, \tag{6}$$

where

$SPL(f)$ = external acoustic sound pressure level (db re 2×10^{-4} μbar),

w = average vehicle skin density parameter (lb/ft^2), and

$TF(f)$ = acoustic transfer function, shown in Fig. 8.

TABLE 2

Prediction of Average (50 Percentile) Lift-Off Vibration by Acoustic Acceptance Method

①	②[a]	③[b]	④	⑤[c]
1/3 Octave Band Center Frequency (cps)	Adaptor Acoustic Accept-ance, H (db)	Lift-Off Acoustic Sound Pressure Level (db re 2×10^{-4} μbar)	1/3 Octave Band Adaptor Vibration ② + ③ (db re 1 g)	1 cps Band Adaptor Vibration ④ + Δ (db re 1 g^2/cps)
200	-140	133.8	-6.2	-22.7
250	-137	134.2	-2.8	-20.3
315	-135	134.2	-0.8	-19.3
400	-137	134.2	-2.8	-22.3
500	-126	133.0	7.0	-13.5
630	-129	130.8	1.8	-19.7
800	-125	129.2	4.2	-18.3
1000	-127	129.0	2.0	-21.5
1250	-128	128.7	0.7	-23.8
1600	-132	128.5	-3.5	-29.0

[a]From Fig. 8.
[b]From Fig. 9 (Atlas/Mercury data).
[c]Bandwidth correction: $(db)_{1\,cps} = (db)_{1/3} - 10 \log_{10} [\Delta f_{1/3}/1]$, $\Delta = -10 \log_{10} (\Delta f_{1/3})$.

TABLE 3

Prediction of Average (50 Percentile) Transonic Vibration by Acoustic Acceptance Method

①	②[a]	③[b]	④	⑤[c]
1/3 Octave Band Center Frequency (cps)	Adaptor Acoustic Accept-ance, H (db)	Transonic Acoustic Sound Pressure Level (db re 2×10^{-4} μbar)	1/3 Octave Band Adaptor Vibration ② + ③ (db re 1 g)	1 cps Band Adaptor Vibration ④ + Δ (db re 1 g^2/cps)
200	-140	136.2	-3.8	-20.3
400	-137	139.2	2.2	-17.3
630	-129	141.2	11.2	-10.3
800	-125	142.2	17.2	-5.3
1000	-127	143.2	16.2	-7.3
1250	-128	144.2	16.2	-8.3

[a]From Fig. 8.
[b]From Table 1. Scaled wind tunnel data.
[c]Bandwidth correction factor as in Table 2.

Calculations for the average lift-off and transonic vibration spectra for the spacecraft adaptor, using Franken's method, are shown in Tables 4 and 5.

It is noted that the adaptor acoustic acceptance during transonic flight is likely to differ from that at lift-off since the mechanism by which the shroud/adaptor is excited is thought to be different. However, at this writing the acoustic acceptances obtained from the ground simulation and used in these calculations represent the only available data.

TABLE 4
Prediction of Average (50 Percentile) Lift-Off Vibration by Franken's Method

①	②	③[a]	④[b]	⑤[c]	⑥	⑦	⑧	⑨	⑩
$f_{1/3}$	$\Delta f_{1/3}$	$SPL_{1/3}$	③ - 20 $\log_{10}$ w	TF	④ + ⑤	⑥/20	g = $10^{⑦}$	⑧²/② g^2/cps	1 cps Band Adaptor Vibration 10 $\log_{10}$ ⑨ (db re 1 g^2/cps)
200	46	133.8	121.8	-137.5	-15.7	-0.785	0.164	0.0006	-32.2
400	92	134.2	122.2	-131.0	-8.8	-0.440	0.364	0.00145	-28.3
630	146	130.8	118.8	-125.0	-6.2	-0.310	0.490	0.00164	-27.9
800	183	129.2	117.2	-122.0	-4.8	-0.240	0.574	0.0018	-27.3
1000	230	129.0	117.0	-121.0	-4.0	-0.200	0.630	0.00174	-27.4
1250	290	128.7	116.7	-121.5	-4.8	-0.240	0.576	0.00113	-29.5

[a]From Fig. 9 (Atlas/Mercury data).
[b]w taken as 4 lb/sq ft.
[c]Mean value of Fig. 10, vehicle diameter = 5 ft.

TABLE 5
Prediction of Average (50 Percentile) Transonic Vibration by Franken's Method

①	②	③[a]	④[b]	⑤[c]	⑥	⑦	⑧	⑨	⑩
$f_{1/3}$	$\Delta f_{1/3}$	$SPL_{1/3}$	③ - 20 $\log_{10}$ w	TF	④ + ⑤	⑥/20	g = $10^{⑦}$	⑧²/② g^2/cps	1 cps Band Adaptor Vibration 10 $\log_{10}$ ⑨ (db re 1 g^2/cps)
200	46	136.2	124.2	-137.5	-13.8	-0.665	0.217	0.0010	-30
400	92	139.2	127.2	-131.0	-3.8	-0.190	0.64	0.0045	-23.5
630	146	141.2	129.2	-125.0	4.2	0.210	1.62	0.0180	-17.5
800	183	142.2	130.2	-122.0	8.2	0.410	2.57	0.0360	-14.4
1000	230	143.2	131.2	-121.0	10.2	0.510	3.24	0.0457	-13.4
1250	290	144.2	132.2	-121.5	10.7	0.535	3.43	0.0407	-13.9

[a]From Table 1. Scaled wind tunnel data.
[b]w taken as 4 lb/sq ft.
[c]Mean value of Fig. 10, vehicle diameter = 5 ft.

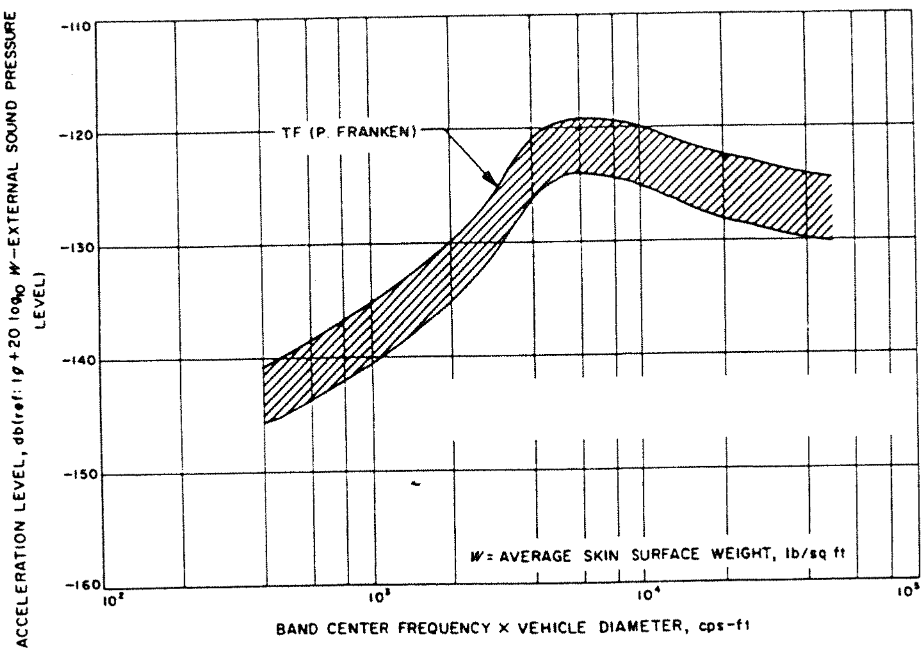

Fig. 10. Generalized relation between external noise and radial vibration. (Reprinted from "Journal of the Acoustical Society of America," Volume 34, No. 4, 1962.)

Predicted Spacecraft Bus Vibration

Prior to flight, an attempt to estimate the spacecraft bus lift-off and transonic vibration was made by adjusting the adaptor estimate (computed using Franken's method) with the approximate envelope of the measured spectra ratio of Fig. 4 (Figs. 17 and 18).

CORRELATION

Spacecraft Instrumentation System

Mariners III and IV carried an identical complement of instrumentation for the measurement of inflight vibration data. The accelerometers in the adaptor provided one radial and two tangential low frequency measurements. The tangential measurements were located 180 degrees apart, so that torsional as well as lateral oscillations were detectable. Particular commentary on these data are beyond the scope of this paper. The two pairing accelerometers of interest to this paper were mounted at the Agena D/spacecraft adaptor interface and at a remote location in the spacecraft bus, sensitive to oscillations in the missile longitudinal axes. Both these were high frequency channels, and were attached to "rigid structure," thus providing valid information regarding total vehicle oscillations, and not characteristics of a resonant accelerometer mount.

Data Analysis

The continuous telemetered accelerometer signals were recorded in FM-Multiplex on magnetic tape. The following types of analysis of the measured data were then performed (9):

Band Pass Analysis — Band pass analyses of the raw flight data from lift-off through transonic were performed at approximately 3 x IRIG frequencies for the high frequency channels. An examination of the data indicates the majority of the vibration experienced was in the 500-800 cps range, and the duration of transonic excitation was significantly longer than that experienced by any Ranger vehicle.

Power Spectral Density Analysis — A 2-1/2-sec time sample was selected at lift-off, in order to obtain PSD's of the high frequency channels. The occurrence of an extremely long portion of vibration during transonic permitted the selection of much longer time sample, and for the data presented here, a 4 sec period was selected. The analysis bandwidth was either 13.5 or 20 cps, depending upon the sample selected.

Acoustic Data Analysis — Spectral analyses of the lift-off acoustic data are included. The data were acquired by two microphones on the umbilical tower, and two microphones on a ground lamppost. Figure 11 shows their locations relative to the launch vehicle.

The plots are particularly descriptive of the wideband dropoff in frequency which is prevalent in this type of data. Resolution of the digital data was initially held to 20 cps and later converted to one-third octave band to be comparable to previous flight acoustic data.

Comparison with Flight

Figure 12 is the time history of acceleration measured on the spacecraft adaptor during ascent of Mariners III and IV.

Sound Pressure Level spectrum and Acoustic Acceptance spectrum are shown in Figs. 13 and 14. The acoustic acceptance plot is the ratio of the adaptor accelerometer PSD to the mean SPL of the tower microphones.

Lift-off calculations assumed the direct applicability of launch tower acoustic measurements obtained from the NASA Atlas/Mercury program. The transonic calculations were based on the scaled wind tunnel results.

Upon analysis of the Mariner flight data, several deviations in some of the estimating parameters and the flight data were discovered: (a) the lift-off acoustic environment deviated from the Atlas/Mercury spectrum at certain frequencies, (b) the adaptor acoustic acceptance calculated from the flight data did not correlate

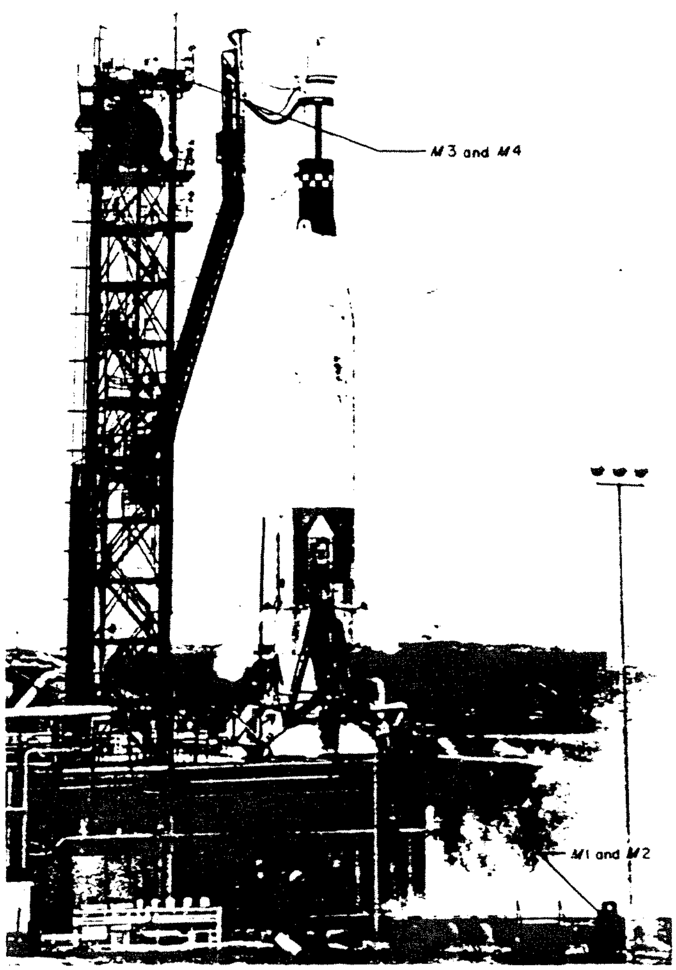

Fig. 11. Mariner III launch pad acoustic instrumentation (Kennedy Space Center launch complex 13)

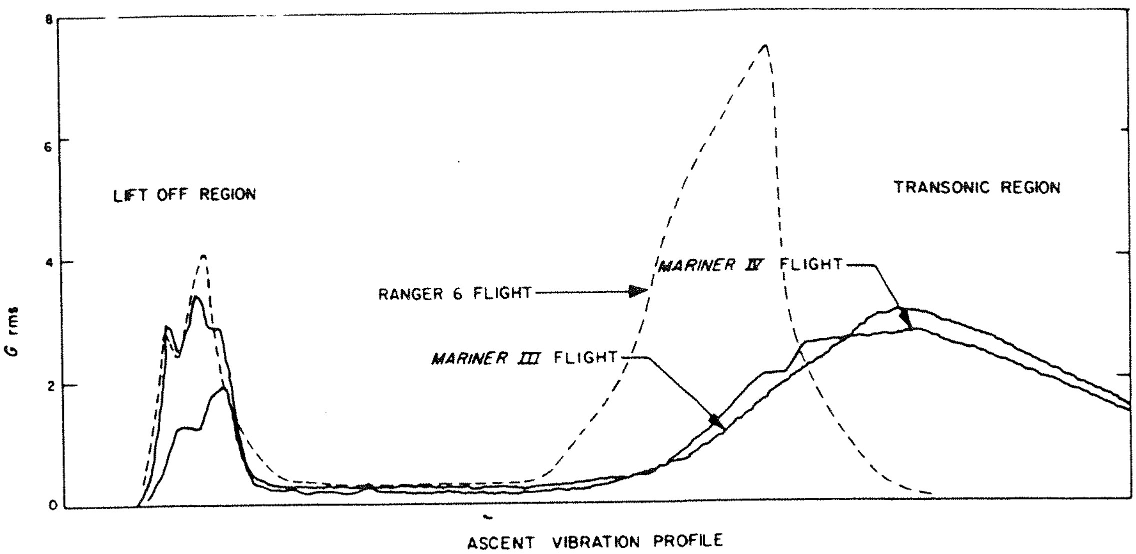

Fig. 12. Mariners III and IV ascent vibration profile (spacecraft adaptor)

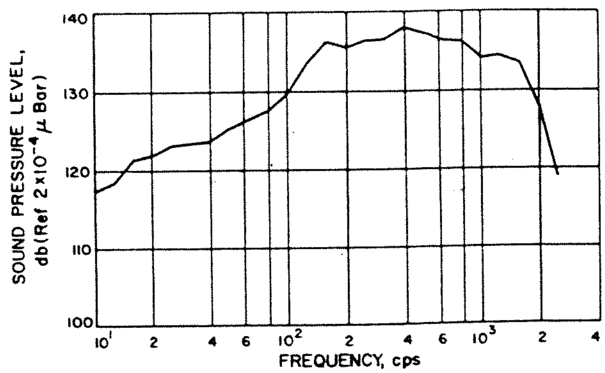

Fig. 13. Mariner III measured lift-off 1/3 octave band acoustic spectra based on the mean SPL of the tower microphones

with the laboratory simulation, and (c) the spectra ratio of the bus to adaptor flight measurements is markedly different during lift-off and transonic.

The SPL and acceptance inconsistencies are tabulated in Table 6. Only the Mariner III flight data were considered, since the original predictions were based on the behavior of the fibreglass shroud. Due to the failure of the Mariner III shroud system, Mariner IV was launched with an all-metal shroud of assumed different dynamic character.

Using the corrected parameters from Table 6, the preflight estimates for the adaptor were re-calculated, and are illustrated in Figs. 15 and 16, in comparison with the flight measurements. The "corrected predictions" were obtained by multiplying the preflight vibration predictions by the ratio of the inflight adaptor acceptance to the ground measured acceptance, and by the ratio of the actual lift-off acoustic level to the assumed Mercury/Atlas level as each parameter appeared in the prediction calculations. This procedure is somewhat artificial but illustrates the requirement for accurate estimating parameters.

Figures 17 and 18 show the initial estimates (uncorrected) for the spacecraft bus vibration, and are compared with Mariner III and IV flight measurements for lift-off and transonic.

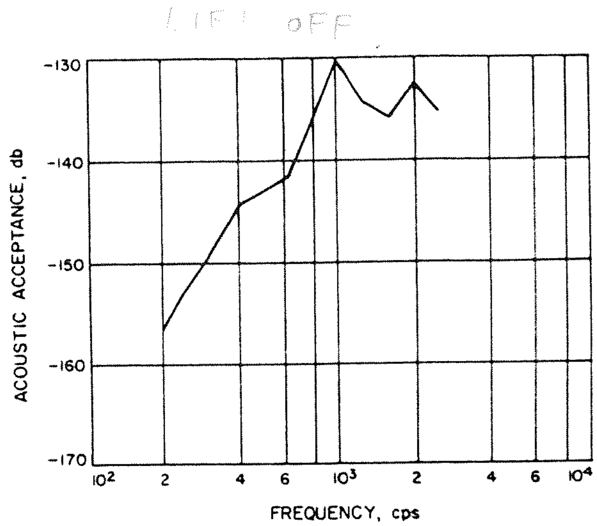

Fig. 14. Mariner III lift-off 1/3 octave band acoustic acceptance — ratio of adaptor accelerometer PSD to mean SPL of the tower microphones

TABLE 6

Comparison of Pre-Flight Estimated and Flight Measured Vibration Prediction Parameters

$f_{1/3}$ (cps)	Lift-Off SPL (db re 2×10^{-4} μbar)			Adaptor Acoustic Acceptance (db)		
	Atlas/ Mercury	Measured Mariner III	Delta SPL	Acoustic Test	Computed Mariner III	Delta H(f)
200	133.8	135.5	1.7	-140	-156	-16
400	134.2	138	3.8	-137	-144	-7
630	130.8	136.5	5.7	-129	-141.6	-12.6
800	129.2	136.5	7.3	-125	-135	-10
1000	129.0	134.2	5.2	-127	-130	-3
1250	128.7	134.5	5.8	-128	-134	-6

While the corrected spectra for the adaptor agree reasonably well with the flight data at lift-off, the high transonic predictions obtained by both methods suggest that certain limitations still exist in the estimating parameters, warranting further study.

As discussed earlier, the transonic pressure fluctuations, derived from the scale model wind-tunnel tests, were based on a preliminary data analysis. Additional analysis of these data is required, since a review of the Mariner flight wideband vibration time histories suggests the presence of strong pressure fluctuations in the supersonic Mach number range beyond the scope of the preliminary analysis. Further, there still exists some reservation as to the validity of the tunnel data.

The wideband transonic vibration build-up and duration observed on both Mariner ascent profiles were unlike that experienced during any Ranger flight, where the transonic vibration was characterized by a very rapid build-up, followed by a sharp decay. The implication is that the validity of extrapolating these data to "similar" vehicles should be questioned.

Figures 19 and 20 are the spectra ratios of the bus to adaptor vibration during lift-off and

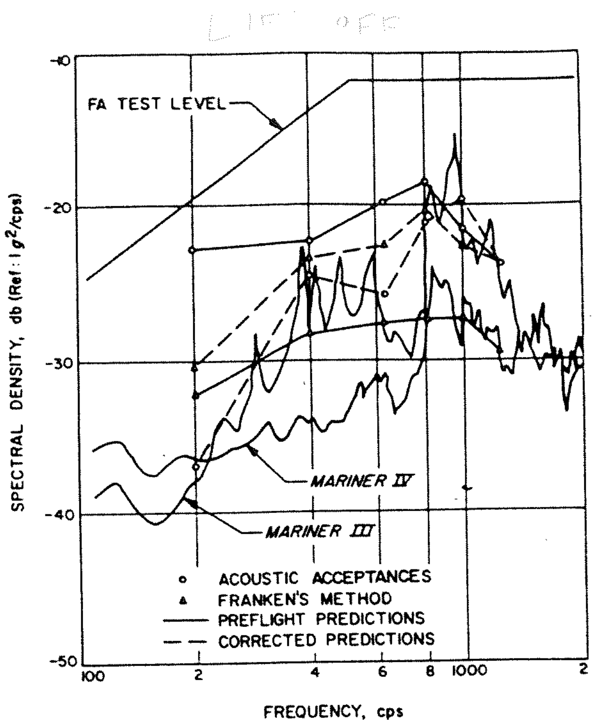

Fig. 15. Comparison of the preflight and corrected predictions for the adaptor average vibration with Mariners III and IV at lift-off

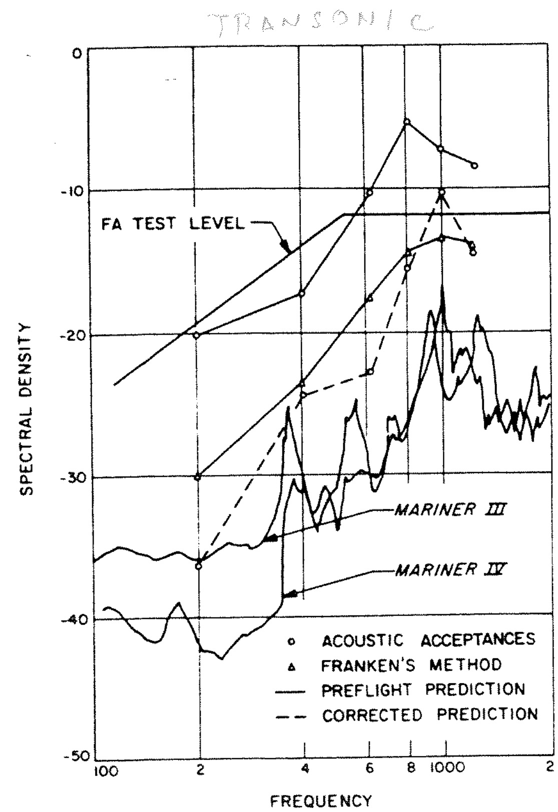

Fig. 16. Comparison of the preflight and corrected predictions for the adaptor average vibration with Mariners III and IV at transonic

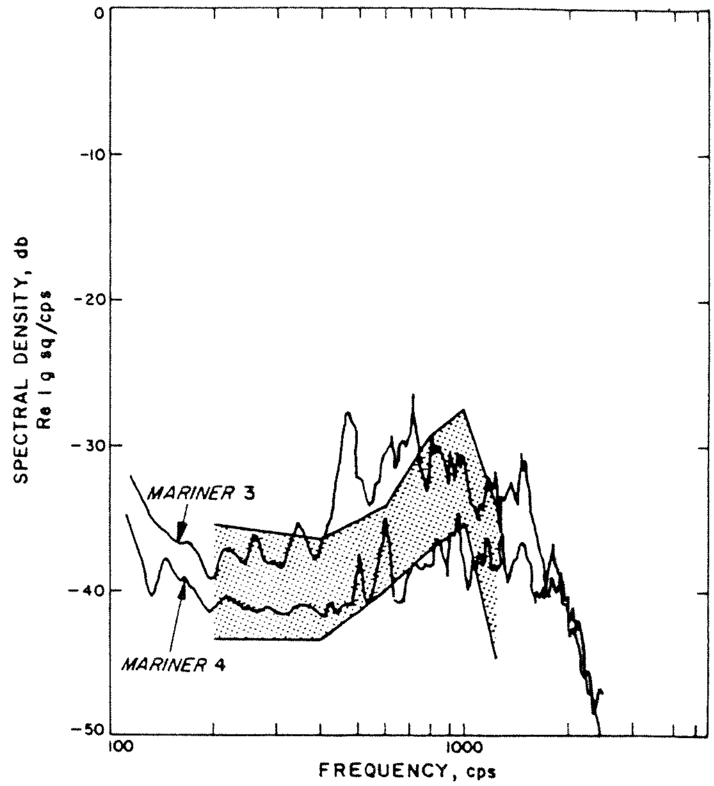

Fig. 17. Comparison of predicted bus average vibration with Mariners III and IV flight measurements at lift-off

transonic for both Mariners III and IV. These ratios are indeed different during the two environments of interest, indicating that the mechanism of excitation differs, as previously noted. Further, the changing of the structural configuration of the shroud does not seem to affect this conclusion. Finally, comparing these "transfer functions" with those obtained from the ground vibration simulation (Fig. 4), it appears that the nature of vibrational response to acoustic excitation may require a degree of simulation unobtainable, except under a flight condition.

Prediction of 95th Percentile Vibration Levels

All preceding calculations were based on average (50 percentile) responses. To apply these data in the consideration of vibration test specification levels, it is necessary to consider the corresponding 95th percentile levels. The analysis of substantial Ranger ground test and flight data suggests that about +6 db should be added to the 50 percentile level data in order to cover the 95th percentile level, and to account for "peaking."

This procedure is suggested for developing vibration test specification levels, i.e., estimate the average (50 percentile) flight vibration, using prediction methods such as described here, then add +6 db to obtain the 95 percentile level and generously envelop this value to prescribe the test requirement.

Verification of Testing Adequacy

The predicted vibration levels for flight have been compared with the measurements. These predictions helped to assess the adequacy of the Mariner spacecraft system vibration test requirements. During the formal qualification and flight acceptance testing, each Mariner vehicle was equipped with a full complement of flight dynamic instrumentation, which was continuously monitored. The adequacy of the vibration test program is best demonstrated by Fig. 21, which clearly illustrates the degree of conservatism inherent in the imposed

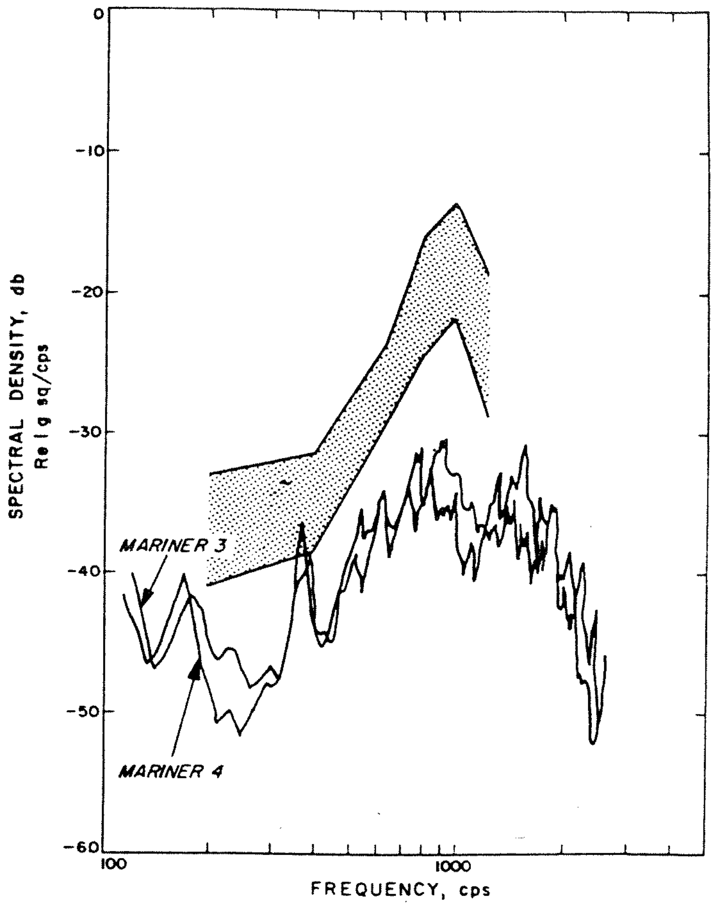

Fig. 18. Comparison of predicted bus average vibration with Mariners III and IV flight measurements at transonic

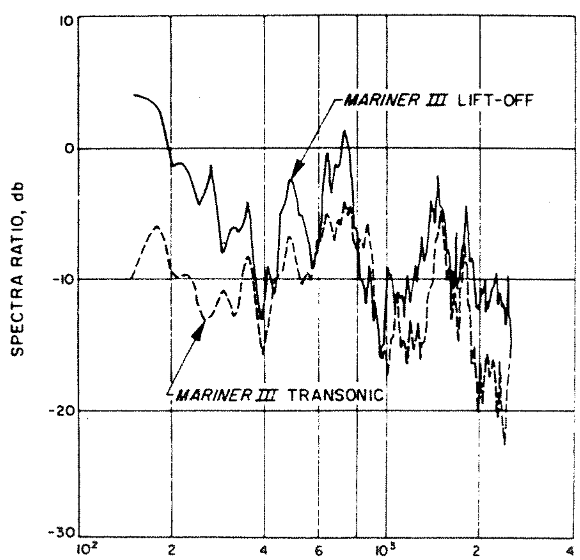

Fig. 19. Spectra ratio of spacecraft bus response to adaptor response for Mariner III at lift-off and transonic

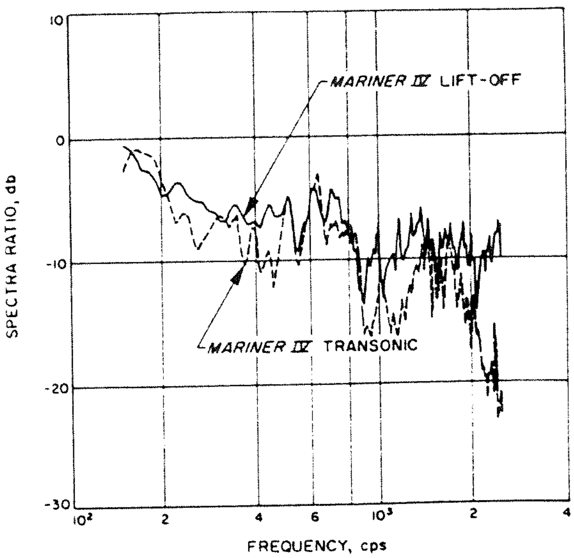

Fig. 20. Spectra ratio of spacecraft bus response to adaptor response for Mariner IV at lift-off and transonic

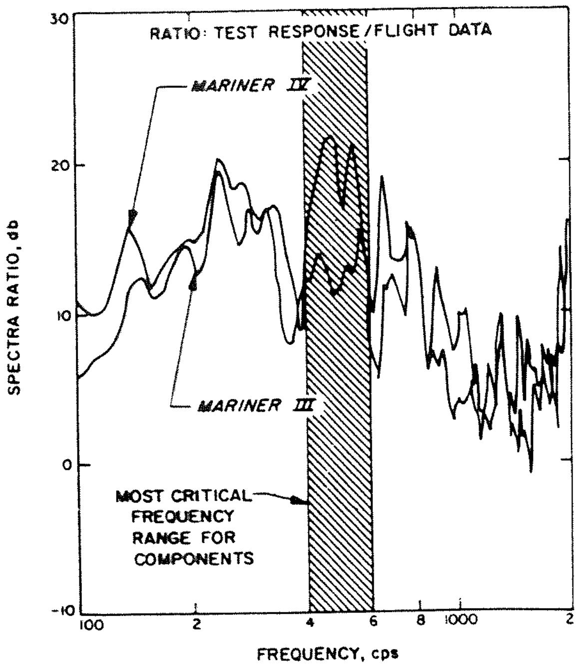

Fig. 21. Ratio of flight acceptance roll axis vibration test response to Mariners III and IV maximum flight measurements

requirements, by expressing the spectra ratios of the spacecraft adaptor ground test responses to the corresponding maximum levels recorded during flight.

CONCLUDING REMARKS

Finally, the Mariner vibration requirements have been reviewed in the light of the data presented and the rationale by which the levels were established. Although these levels were based on observed inflight vibration obtained from Ranger, together with some appropriate wind tunnel tests and auxiliary calculations, they were questioned to the end. The spacecraft acceptance tests, established by enveloping the Ranger 95th percentile probability level, were never exceeded in flight. The TA levels, accomplished by scaling in such a way that the ratio to the FA tests was approximately 5 to 3, appear to have developed sufficient conservatism for vehicle qualification. However, in critiquing this work, such factors of concern throughout the Mariner development were:

1. At the time of the establishment of the levels, no vibration measurements had been obtained inside any inflight spacecraft. In addition, there were no flight data for the Mariner configuration, and analysis indicated that the shroud shape would strongly affect the vibration characteristics.

2. Although the overall rms value of the observed launch vehicle inflight vibration has been quite similar from flight to flight, the spectrum is known to be quite variable.

3. Testing of the vehicle on the ground is grossly affected by the technique and the fixture transfer functions which modify the input spectrum.

In consideration of the above, it appears necessary that steps to cope with these difficulties be taken in the future in the following areas:

1. A large effort should be expended in order to obtain inflight vibration measurements, both inside spacecraft and on the launch vehicle.

2. To compensate for testing problems, such techniques as multiple shaker systems, improved equalization techniques, etc., should be studied in order to increase the dimensions in which the vibration testing technique can be controlled.

3. Due to the present state-of-the-art in estimating environmental vibration, and since future programs will be faced with the "same

old problem" of prescribing qualification testing levels at early dates with little available information, it appears highly desirable to require a series of tests of the prototype vehicle at increasing levels over the qualification requirements at an early date in the program. This test would indicate what design margin actually exists. It would be invaluable to know just how much inherent, but untested, margin there is in a typical design, when the need for trade-offs arises late in the program. Weak sisters in the chain would also be immediately pointed out, and depending on the margin demonstrated, could be changed or redesigned at a stage in development when such tasks are easily accomplished.

4. Further study and development of estimating and analysis techniques are definitely warranted. Work in areas such as model scaling, wind tunnel analysis, and acoustical testing of spacecraft should be emphasized to better understand the manner in which the mechanism of vibration is effected, and how it is transmitted into and throughout the spacecraft. Specific emphasis should be placed on obtaining estimates of the response and transfer characteristics for complex electronic systems due to acoustical excitation.

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DISCUSSION

Mr. Varga (Hughes Aircraft Co.): In one of your first charts you had an envelope of some flight data. Was this taken from the early models of the Mariner or Ranger?

Mr. Hyde: We took the envelope of the 95th percentile data from Rangers 1 through 5 — five flight vehicles. That envelope became the Mariner flight acceptance test requirement.

Mr. Varga: Were these levels which you set for your FAT and your qualification levels comparable to a TAT?

Mr. Hyde: Yes.

Mr. Varga: You said that was 4-1/2 db. How did you arrive at the 4-1/2 db, which is something like three times the sound intensity?

Mr. Hyde: There have always been questions raised about the margin to be allowed between the qualification level and that expected as an acceptance test level. In the past, we at JPL have used a factor of about 3 db; I think Ranger used 3 db. It is an estimate based upon experience. There was enough uncertainty about the new Mariner vehicle compared to Ranger that we did not feel 3 db was an adequate margin, so we set it at 4-1/2 db.

Mr. Varga: Were you able to correct these predictions then as you went on with Mariner 1 and 2? Did you get data from Mariner 1 and 2?

Mr. Hyde: Mariner 1 and 2 were very similar to Ranger vehicles in configuration. We did not fly any onboard instrumentation on Mariner 1 and 2. We did have onboard instrumentation on Mariner 3 and 4.

Mr. Lyon (Bolt, Beranek & Newman): What was the basis of the cross hatched section in one of the curves where it showed the components critical in this frequency range?

Mr. Hyde: That again was based on experience gained with the subsystems with which we have been dealing at JPL. Mariner has evolved from the Ranger class of vehicle. They use essentially the same subsystems, with minor modifications. We found on the early Rangers and on the early Mariners that the critical range for the electronic subsystems was 400-500 cps.

* * *