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# TECHNICAL NOTE

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# BALANCING VANGUARD SATELLITES


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## SUMMARY

The Vanguard satellites and component parts were balanced within the specified limits by using a Gisholt Type-S balancer in combination with a portable International Research and Development vibration analyzer and filter, with low-frequency pickups. Equipment and procedures used for balancing are described; and the determination of residual imbalance is accomplished by two methods: calculation, and graphical interpretation. Between-the-bearings balancing is recommended for future balancing of payloads.

CONTENTS

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D-498

## INTRODUCTION

The Vanguard third-stage rocket is spin-stabilized to insure directional stability during the burning period. The spin velocity of approximately 200 rpm is imparted by two small solid-propellant rockets mounted on the spin table that axially supports the third-stage rocket-satellite combination within the forward section of the second stage.

The third stage has four radial support arms attached to the outer race of the forward spin bearings (Figures 1 and 2). These arms are jettisoned as the retrorockets retard the second stage allowing the third stage to emerge. The satellite is also mounted on the outer race of the spin bearing; as soon as the race is freed, the satellite begins to acquire spin because of bearing friction. Both the third stage and the satellite must be statically and dynamically balanced in order to minimize flight-path errors during third-stage burning.

Early in the Vanguard program a limit of imbalance for the satellie payload was fixed at 2 ounce-inches; this is a static tolerance. No specification was set for the dynamic imbalance of the payload. Each payload was balanced both statically and dynamically to the limiting accuracy of the balancing equipment.

## EQUIPMENT

### Type

A combination of the Gisholt Dynetric Balancer (Type-S), and the International Research and Development Corporation (IRD) Vibration Analyzer (Model 652LF) and Filter (Model 1064) was employed to balance the satellites. The Gisholt machine was used to support and revolve a special tubular-steel balancing arbor from which the satellites were cantilevered. The special Teflon half-bearings, located 28 inches apart center-to-center, were used in the Gisholt suspension to support the arbor (Figure 3).

Located at each bearing point was an IRD magnetic-core low-frequency vibration pickup with maximum response above 300 rpm. The angular speed used for balancing all Vanguard satellites was 322 rpm, which lies well within the frequency range of these pickups (Figure 4).

A switch was used to permit convenient monitoring of either pickup. After filtering by a bandpass filter to eliminate extraneous vibration frequencies (Figure 5), the signal passed on to the vibration analyzer, and was utilized for firing a stroboscopic light every revolution to indicate the frequency (which remained constant) and the amplitude of vibration.

## Limitations



It was not possible to balance dynamically either the test vehicle payload spheres* (e.g., Vanguard I) or the separation mechanisms; the system sensitivity was inadequate to detect correction-plane differences of 2 or 3 inches at the low mass levels involved. However, static balancing of these small units was accomplished very satisfactorily. Although a 50-pound payload was the largest Vanguard payload balanced, a 100-pound payload probably could be balanced with the existing system after minor modification.

To accommodate the Vanguard satellite with antennas extended, it was necessary to raise the Gishold machine an additional foot. This resulted in a swing clearance of approximately 4 feet. With the required 4-foot swing, the satellite could not be supported between the bearings on the existing Gishold Type-S machine. Therefore, it was necessary to cantilever the satellite off one end of the machine.

The accuracy of the system permitted balancing the Vanguard satellites to a limit of 0.25 ± 0.1 ounce-inch maximum imbalance. The test-vehicle spheres and separation devices could be balanced to 0.1 ± 0.05 ounce-inch. Because of interchangeability requirements and other variables, these lower limits were not realized with flight assemblies. The final balance values measured for the Vanguard satellites are summarized in Appendix A.

*The 6.4-inch "minimal" satellites employed as payloads in the Vanguard Test Vehicle series.

# BALANCING PROCEDURES

## General Method

The first step in any balancing operations is to make certain that the basic system used for balancing is operating properly and the arbor is extremely well balanced. In order to obtain the desired rotational speed of the arbor, the diameters of the driver (at the motor) and the wheel (mounted on the arbor) were machined. The arbor speed was checked by using a small photocell and a light source. The cell was mounted opposite a hole in the end plate of the arbor, and a light source was placed facing it on the opposite side of the plate. The output from the photocell was fed into a Hewlett-Packard frequency counter. A rotational speed of 322 rpm was obtained very accurately in this fashion.

Several types of drive belts were tested; a thin woven-cloth belt, 1 inch wide, manufactured by the Globe Woven Belting (Buffalo, New York) was selected as the most suitable, since a minimum slippage and vibration resulted. The wheel (mounted on the arbor) was slightly crowned to keep the belt centered and to prevent runoff.

The drive motor was started by a foot switch, and the belt was engaged by lowering a handle connected with the idler pulleys. The bearings were locked during startup; as soon as the arbor was up to speed, one or both were unlocked. Amplitude readings could be made at each bearing by an arrangement that permitted switching from one pickup to the other. These pickups were mounted on the floating bearing blocks.

In all cases the satellites were balanced by placing them on a balanced standard satellite separation mechanism* mounted on the arbor. This device was centered and checked to prevent the introduction of errors (Figure 6).

When the checks on the basic system were completed, the unit to be balanced was installed on the separation device. Prior to installation, a thorough inspection of the sphere was made to verify that all wiring and components were in position and firmly attached. Early balancing studies yielded a systematic method for balancing the satellites on the system described. This basic approach consists of adding correction weights in three planes, i.e., in the equatorial plane (static), in the plane 45 degrees N and in the plane 45 degrees S. The procedure is briefly described as follows (Figure 6):

(1) Spin unit, and record phase and amplitude readings for each bearing.

(2) Add a single weight (about 20 grams) in equatorial plane at a point 90 degrees clockwise from phase reading of left bearing.

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*Baumann, R. C., "Vanguard Satellite Separation Mechanisms," NASA Technical Note D-497, in publication (1960)

(3) Spin unit with only left bearing unlocked, and note phase and amplitude readings. Adjust counterweight in amount and position until amplitude has dropped into the range of 0.001 - 0.002 inch and phase is essentially that recorded in step (1).

(4) Place one weight (15 grams) in 45-degree N plane and a second of equal amount in 45-degree S plane, so that weights are 180 degrees out-of-phase, to produce a couple effect. Record phase and amplitude readings with both bearings unlocked. Repeat this process eight times, shifting weights 45 degrees around the rotation axis each time.

(5) Select the location of these two weights which yielded a minimum in amplitude readings. Return weights to this location, and adjust amount of each weight until amplitude at each bearing is reduced to the range of 0.001 - 0.002 inch. If necessary, shift position of each weight slightly to lower amplitudes. Phase reading for each bearing should agree closely with reading in step (1).

(6) Replace temporary (clay) weights with permanent lead weights; attach to shell with screws and nuts. Change only one weight at a time. Make lead weights slightly heavier than indicated by calculations, to permit subtracting from permanent weights rather than adding.

(7) Determine residual imbalance in unit, using checkweights of two or three different sizes (e.g., 7.5, 10 grams). Record amplitude readings first with right bearing locked and left bearing unlocked, then with left bearing locked and right bearing unlocked. Repeat process eight times with each checkweight, each time shifting weight 45 degrees around unit in equatorial plane. Determine residual imbalance (see Appendix B).

Although it is possible to correct the imbalance with only two planes of correction, the present method considerably simplified the balancing problem for the particular case of a cantilevered satellite. Between-the-bearings balancing can be readily attained by the two-plane correction method, since the cross-effect between correction planes is generally not too great. The difference in the amount of counterweight needed for each method was calculated and was found to be relatively small.

## Test Vehicle Spheres

The smallness of the test vehicle payloads made it in possible to attain a two-plane correction, since the machine was insufficiently sensitive and could not detect differences between planes located within 3 inches of each other. Consequently, the lead counterweights were added at the "equator" of the sphere. Amplitude and phase readings were taken with one bearing, adjacent to the sphere, unlocked, as this provided sufficient information for a one-plane correction.

## 20-Inch Satellites

The balancing of the 20-inch Vanguard satellites was achieved according to the outlined seven-step procedure.

## 13-Inch Diameter Magnetometer Satellite and Magnetometer X-Ray Satellite



The 13-inch-diameter magnetometer satellite and the magnetometer x-ray satellite (Vanguard III) have chimney-like long extensions (sensor tubes) out of their north poles. The general procedure was modified as follows: The equatorial weight was added as previously described but also a second weight was added at the tip of the magnetometer sensor tube; both weights were manipulated alternately until the desired amplitude level was reached. The residual imbalance was determined with a single checkweight at the equator as in the general method.

## Separation Device (40-Second Timer)

The standard (40-second timer) satellite separation devices* were balanced with a single weight because of their comparatively short length. The principal source of imbalance lay in the heavy g-weight. Each counterweight was located opposite the g-weight and was attached inside the separation device sleeve. Balancing was accomplished with only one bearing unlocked, since this was a static (single-plane) balance.

## Combination of Separation Device (300-Second Timer) and Spin-Retarding Mechanism

This combination was balanced by the method described for separation devices. However, since both components possessed a g-weight, the g-weights were positioned opposite each other. This orientation of the weights reduced the initial imbalance to such an extent that only a small counterweight (about 5 grams) was needed, whereas the separation device required a weight of about 60 grams.

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*Baumann, R.C., "Vanguard Satellite Separation Mechanisms," NASA Technical Note D-497, in publication (1960).

## Radiation Shields

The 14-inch radiation shields used on one satellite were balanced in the same manner as were the separation devices. It was not possible to balance the larger 20-inch-diameter shields with the existing equipment; however, a static balance was achieved by attaching each shield to a small shaft resting on rollers.

# CONCLUSIONS AND RECOMMENDATIONS

The Vanguard satellites and component parts were balanced within the specified limits using the IRD and Gisholt equipment in the manner described. The experience gained in balancing work during the Vanguard program indicates that future balancing of payloads should be accomplished between-the-bearings. In the present arrangement the satellite's weight constituted approximately 25 percent of the total weight revolved. The remaining 75 percent acted as a parasite in that it reduced the machine's sensitivity to imbalance in those objects being balanced. Had the satellites been balanced between bearings, the weight of the supporting member would have been reduced by approximately one-half, raising the sensitivity accordingly. Between-the-bearings balancing also decreases cross-effects in that the operator is permitted considerably more control over the work.

A thorough review of the literature published by manufacturers of balancing equipment revealed two firms whose standard machines seem adaptable for satellite balancing. The Gisholt Machine Company and American Trebel products can be utilized over a relatively broad range of workpieces. For both the immediate and anticipated uses, the type 4U (Gisholt) and Models Dev-60 and Dev-3000 (American Trebel) appear desirable. (Appendix C presents a fairly comprehensive listing of manufacturers and their equipment characteristics.)

The vertical balancing method, which would be extremely desirable in the present application to satellites, has not as yet been adequately developed for most purposes. Three companies, American Trebel, Gisholt, and Tinius Olson, list vertical dynamic balancing machines among their available units. However, these machines are capable of handling only comparatively small objects (50 pounds and 17-inch diameter, maximum); this is a serious limitation. Future requirements may necessitate the use of vertical machines exclusively. It would be of value, therefore, to investigate possible designs for vertical machines.

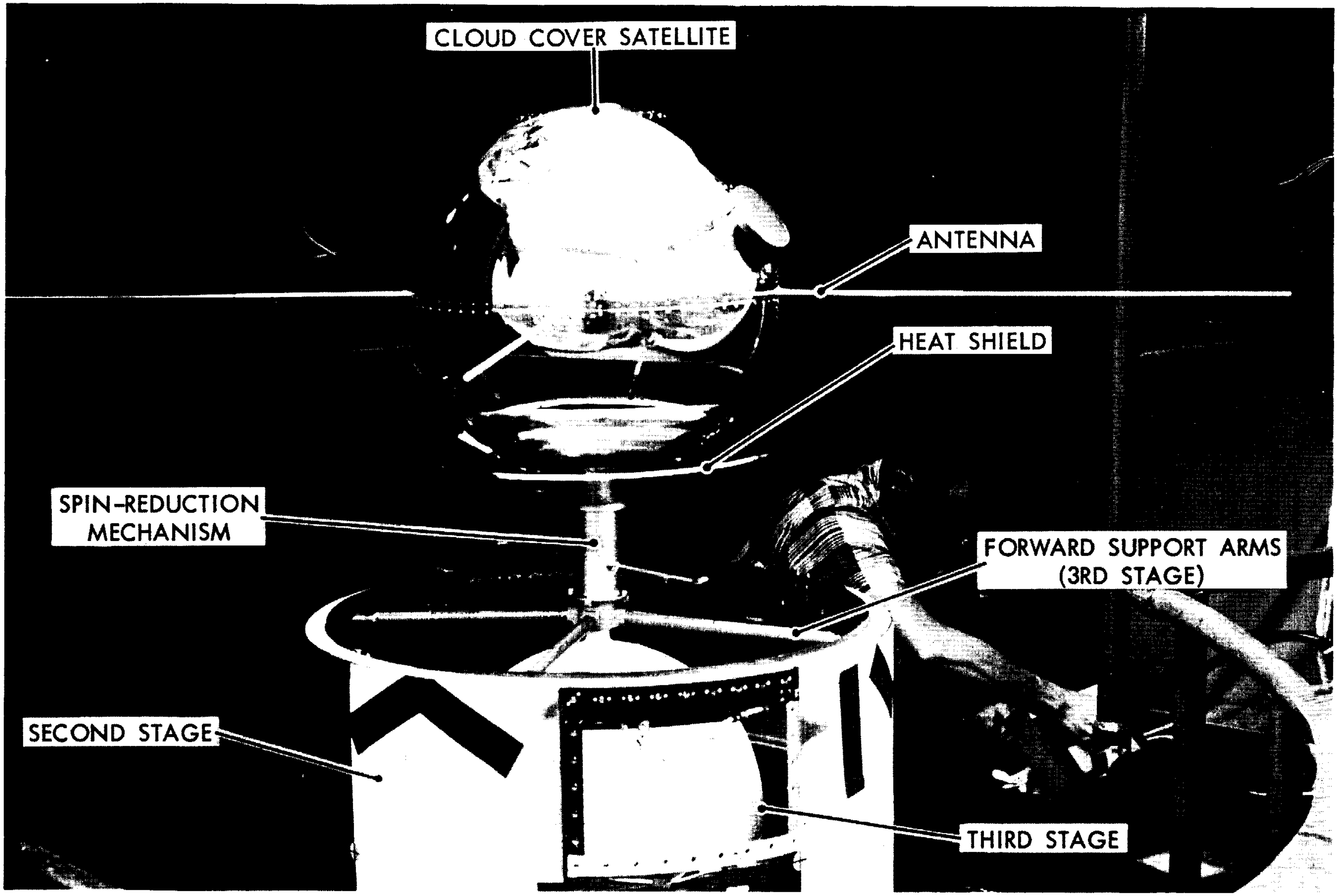
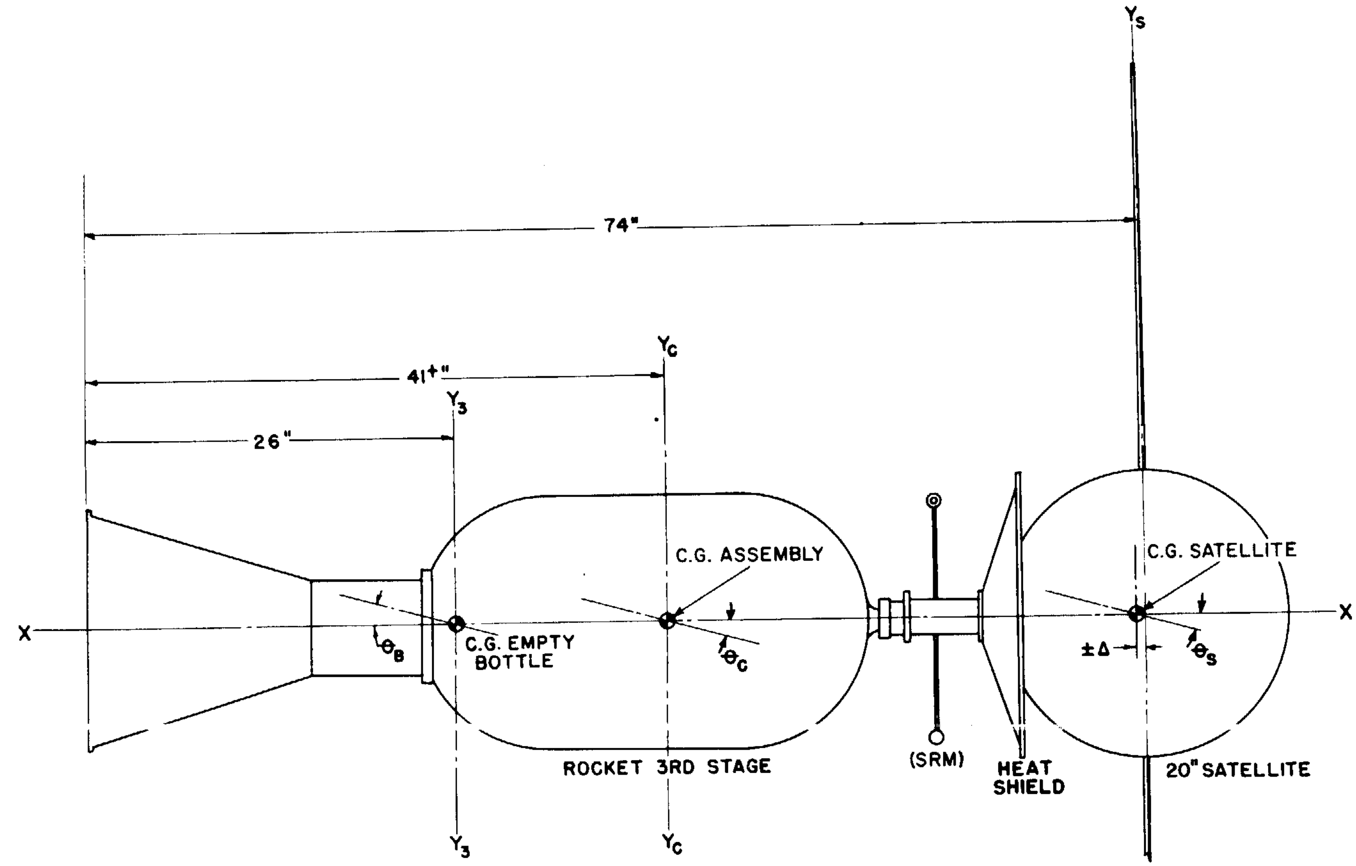



Figure 1 - Cloud cover satellite (Vanguard II) assembled to launching vehicle




APPROX. MOMENTS OF INERTIA (SLUG-IN.$^2$)

| ITEM | X-X | Y-Y |
|---|---|---|
| COMBINATION | 78 | 1465 |
| 3RD STAGE | 55 | 373 |
| SATELLITE | 18 | 19 |
| SRM AND HEAT SHIELD | 5 | — |

APPROX. WEIGHTS (LB)

| ITEM | |
|---|---|
| COMBINATION | 73.5 |
| 3RD STAGE | 50 |
| SATELLITE | 22 |
| SRM | 1.1 |
| HEAT SHIELD | .4 |

Figure 2 - Flight configuration (SLV-3 and SLV-4) prior to satellite separation and after 3rd-stage burnout

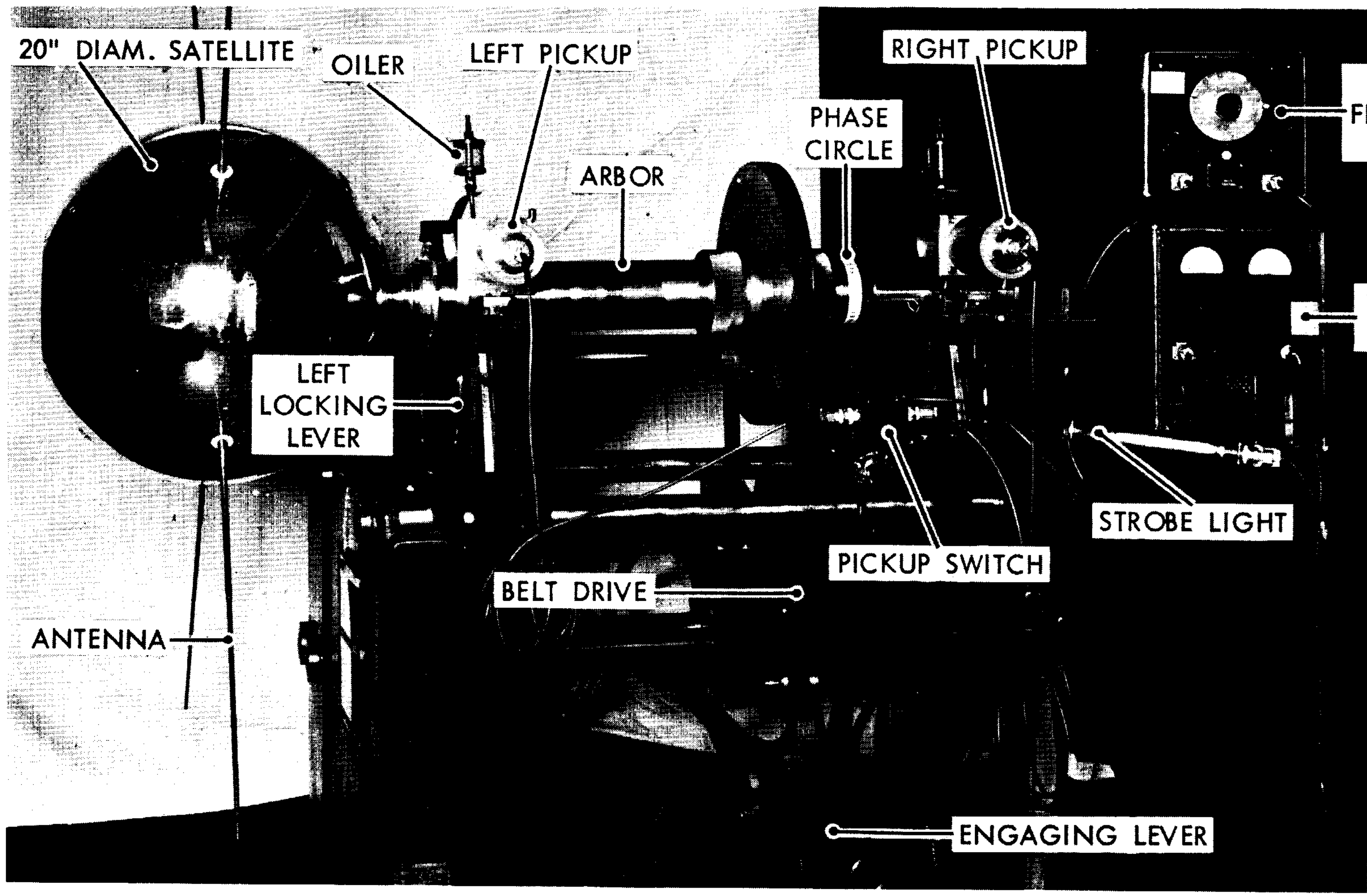



Figure 3 - Balancing equipment used for Vanguard satellites

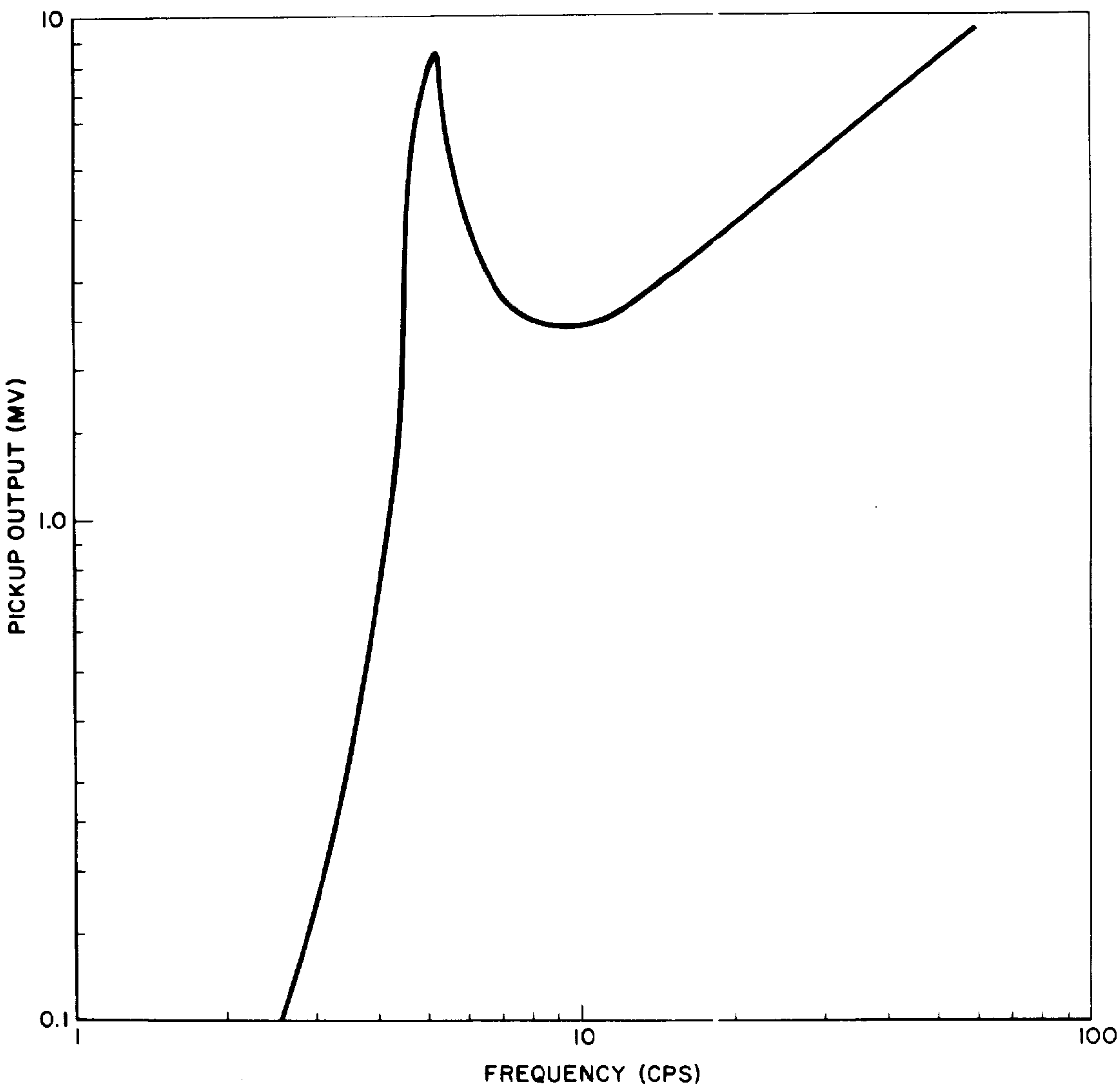



Figure 4 - Output vs. frequency for low-frequency I.R.D. pickup

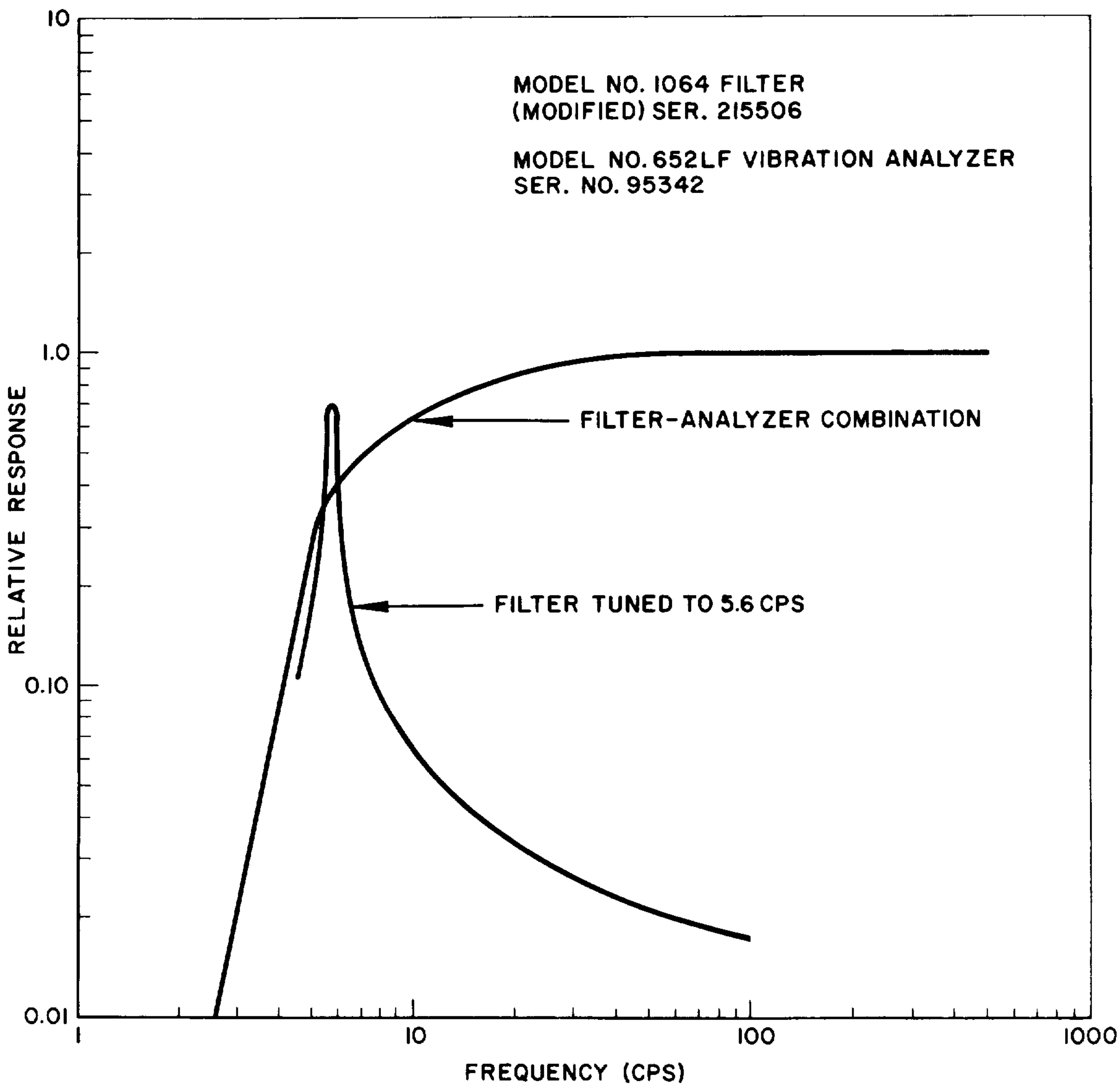
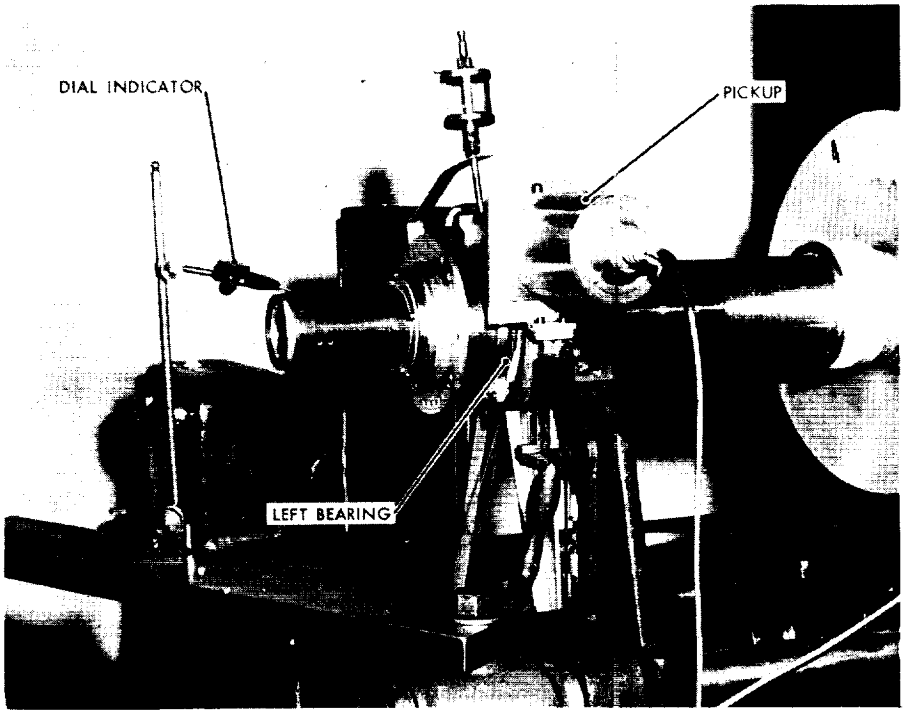
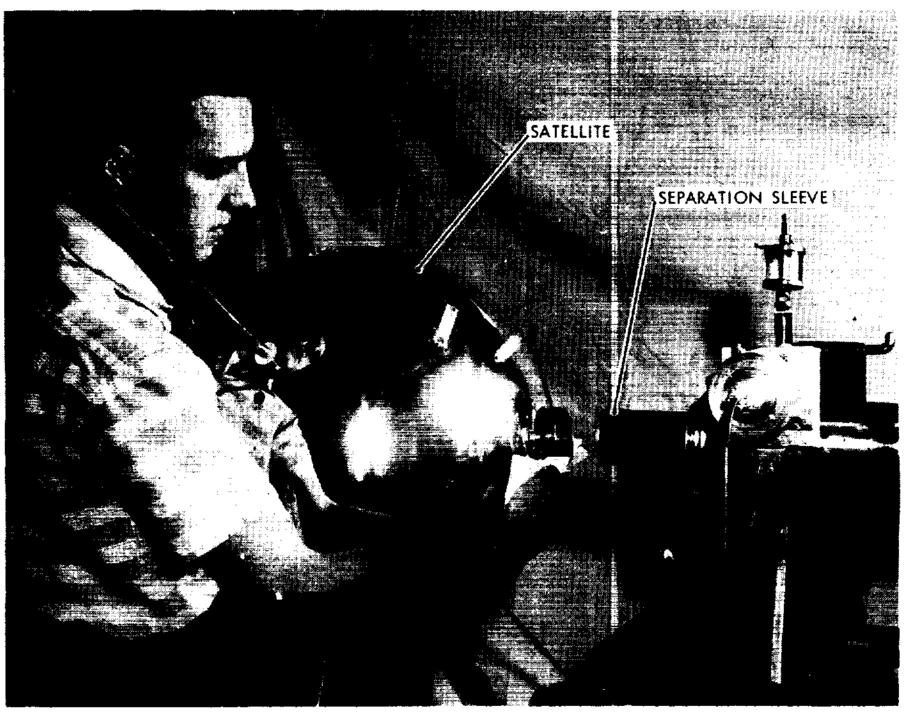



Figure 5 - Relative response vs. frequency for I.R.D. filter and vibration analyzer

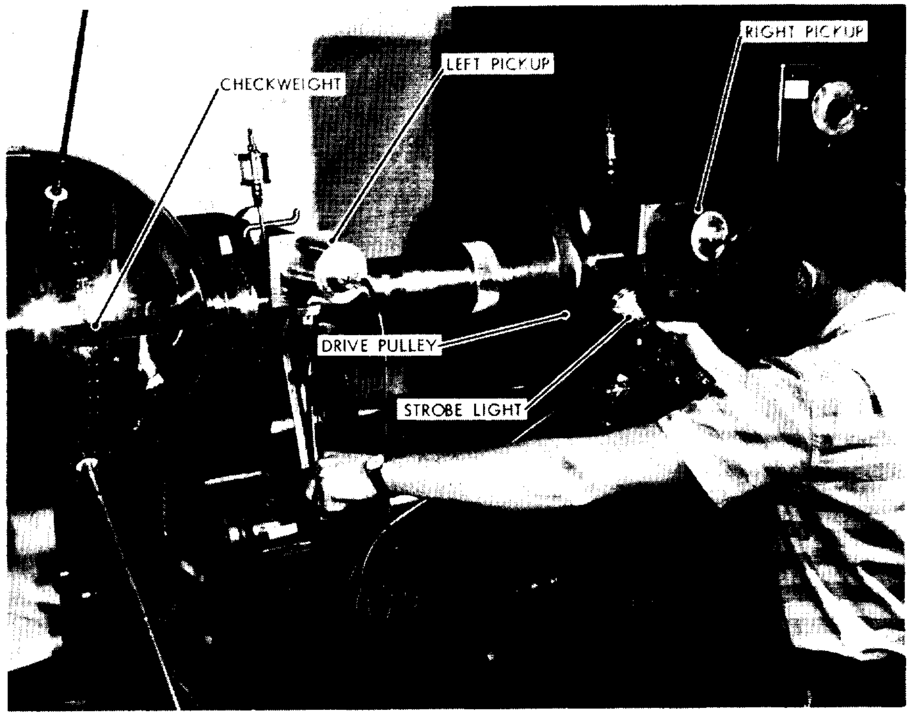



(a) Checking run-out of separation sleeve

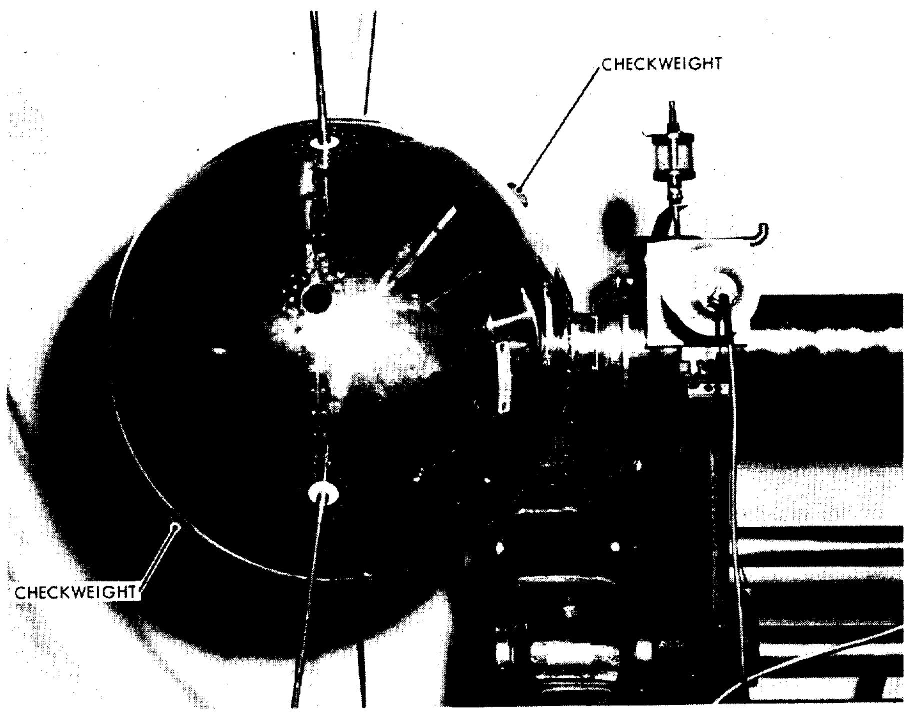



(d) Dynamic-balance determination

Figure 6 - General Balancing Procedure for Vanguard Satellites (continued on next page)




(c) Static-balance determination




(b) Installation of satellite

Figure 6 - General Balancing Procedure for Vanguard Satellites (concluded)

## Appendix A

## TABULATION OF VANGUARD SATELLITES AND DEGREE OF BALANCE OF FLIGHT UNITS

All Vanguard satellite flight units and their residual imbalance are listed below. Data on dynamic imbalance of the Test Vehicle Spheres are not presented, as these units were balanced with only one weight. The relatively low static imbalance of the magnetometer flight unit no. 1 (SLV-5) was made possible by balancing and flying the unit on the same separation mechanism sleeve. The counterweight numbers are for the total weight added to each satellite.



| Vehicle no. | Satellite type and unit no. | Satellite counterweight (lb.) | Residual static (oz-in.) | Imbalance dynamic (oz-in.$^2$) |
|---|---|---|---|---|
| TV3 | Test Vehicle Sphere F* | 0.05 | 0.2 | — |
| TV3BU | Test Vehicle Sphere G* (Life Science) | 0.04 | 0.1 | — |
| TV4 | Test Vehicle Sphere (Vanguard I)* | 0.04 | 0.2 | — |
| TV5 | X-Ray FU #2 | 0.22 | 1.2 | 0.9 |
| SLV1 | Lyman-Alpha FU #3 | 0.33 | 1.4 | 2.1 |
| SLV2 | X-Ray FU #1 | 0.33 | 1.3 | 1.5 |
| SLV3 | Cloud Cover FU #2 | 0.13 | 1.4 | 1.4 |
| SLV4 | Cloud Cover FU #1 (Vanguard II) | 0.15 | 1.6 | 5.5 |
| SLV5 | Magnetometer FU #1 | 0.22 | 0.3 | 1.9 |
| SLV6 | Radiation Balance | 0.29 | 0.5 | 3.1 |
| SLV7 | Magneray | 0.36 | 2.3 | 2.6 |

*6 antennas, solar cell clusters

# Appendix B

## DETERMINATION OF RESIDUAL IMBALANCE

Two methods for determining residual imbalance are discussed herein: by calculation, and by graphical means.

### Calculation Method

*Derivation of equations for calculating imbalance*

The imbalance in a satellite may be represented by a small imaginary weight w offset from the satellite spin axis at some radius r, at a distance L from the plane passing through the satellite center of gravity and perpendicular to the spin axis (Figure B1). Static imbalance of the satellite is given by the product wr, and dynamic imbalance is given by wrL.

If either the left or right bearing is locked, the satellite imbalance will create a resultant moment about the locked bearing, which acts as a pivot point. This moment will act in the same direction relative to the satellite. A weight placed on the periphery of the satellite in any given plane and at various angular positions will be in phase with the imaginary weight at a certain point, and out of phase 180 degrees from this point (Figure B2). These two positions result, respectively, in maximum and minimum amplitude readings. These figures are utilized in setting up a proportion to determine the weight required in the checkweight plane to counterbalance the existing moment of the residual imbalance about the locked bearing.

From Figure B2, it is readily apparent that one-half the difference between the maximum and minimum amplitudes is proportional to the weight needed to counterbalance the moment caused by satellite imbalance, and that the average of the maximum and minimum figures is proportional to the checkweight. Thus

$$\frac{w}{a} = \frac{W}{A} \tag{B1}$$

where

w = weight needed to counterbalance moment,

a = half the difference between maximum and minimum amplitudes,

W = checkweight,

A = average of maximum-minimum amplitudes.

By locking first the right bearing and then the left, two w's ($w_l$ and $w_{rt}$, respectively) are obtained. These w's are used in two simultaneous equations to calculate the static and dynamic imbalance. The equations for the Lyman-Alpha and X-Ray satellites are derived as follows:

For $M = O$ about the right bearing (refer to Figure B1),

$$wr\,(\underbrace{L + 9.25 + 1.1 + 4.1 + 28.1}_{known}) = w_l\,R(\underbrace{10 + 1.1 + 4.1 + 28.1}_{known}),$$

Where R is the radial distance to checkweight center of gravity.

Simplifying the equation and putting $wr = k$ gives

$$kL + 42.5\,k - 43.3\,w_l R = O. \qquad \text{(B2)}$$

Similarly, for $M = O$ about the left bearing,

$$wr\,(L + 9.25 + 1.1 + 4.1) = w_{rt}R\,(10 + 1.1 + 4.1)$$

or

$$kL + 14.4\,k - 15.2\,w_{rt}R = O. \qquad \text{(B3)}$$

Solving Equations B2 and B3 simultaneously gives

$$28.1\,k - 43.3\,w_l R + 15.2\,w_{rt}R = O.$$

Therefore

$$k = 1.54\,w_l R - 0.54\,w_{rt}R \text{ (static)},$$

and

$$kL = 43.3\,w_l R - 42.5\,k \text{ (dynamic)}.$$

Thus, from the data gathered by using a checkweight, calculate $w_l$ and $w_{rt}$ by Equation B1, and use these values to calculate the static and dynamic residual imbalance. For all units except the magnetometer, R is approximately 10 inches. In the case of the magnetometer, R equals 6.5 inches.

*Typical calculation of residual imbalance*

As an example of residual imbalance calculations consider Magnetometer Flight Unit 2, using the data obtained with a 10-gm checkweight. The data are listed as follows:

| Amplitude | |
|---|---|
| Left bearing | Right bearing |
| 9.3 | 12 |
| 9.6 | 12.75 |
| 9.5 | 12.25 |
| 9.3 | 12 |
| 9.0 | 12.25 |
| 9.1 | 12.0 |
| 9.0 | 12.0 |
| 9.2 | 12.5 |

Selecting the maximum and minimum figures in each column and calculating the w for each give:

$$w_l = 0.32 \text{ gm}, \; w_{rt} = 0.31 \text{ gm}.$$

The equations for static and dynamic residual imbalance in the magnetometer satellites are:

$$k = 9.74\, w_l - 3.26\, w_{rt} \text{ (static)},$$

$$kL = 273.5\, w_l - 42.13\, k \text{ (dynamic)}.$$

Using the calculated values of $w_l$ and $w_{rt}$ gives

$k = 2.11$ gm-in., or 0.07 oz-in. (equivalent to 0.00055 in. center-of-gravity displacement); (B4)

and

$$kL = -6.5 \text{ gm-in.}^2, \quad \text{or } -0.23 \text{ oz-in.}^2. \tag{B5}$$

The dynamic imbalance may be positive or negative, depending on the direction of the moment.

## Graphical Method

In order to determine the residual imbalance graphically, it is necessary to have only one set of data; i.e., with the balanced unit rotating and both bearings free, read the phase and amplitude of both right and left bearings. Using pickups and calibration curves (Figure B3), correct the amplitude readings. Lay out to scale on graph paper, the relative bearing positions and center of gravity of the unit being balanced. Select any appropriate scale to represent the amplitude readings. A typical set of readings follows for Magnetometer Satellite Flight Unit 2:

Left amplitude, 0.85; phase, 130 degrees,

Right amplitude, 0.3; phase, 230 degrees.

By using these data, a graphic determination of the satellite center-of-gravity displacement due to imbalance is obtained (Figure B4). Resultant displacements are resolved into two planes (i.e., 0 to 180 degrees, and 90 to 270 degrees) The graphic analysis is done in three views: View A shows the resultant components resolved into the two planes. View B shows how the arbor slope is obtained in each plane. View C shows how the resultant displacement of the center of gravity with respect to satellite mounting plane is obtained. The value obtained for the reading cited is 0.00038 in. displacement. An equivalent static imbalance of 0.124 oz-in. results. This is not the true static, but the combined effect of static and dynamic imbalance at the center of gravity along the spin axis. The calculated values were 0.07 oz-in. in static and -6.5 gm-in.$^2$ (or - 0.23 oz-in.$^2$) dynamic residual (Equations B4 and B5). Although the values obtained by the two methods are not identical, there is reasonable correlation.

D-498

## Conclusions

The balance tolerance of 2 oz-in. (static), imposed by the launch vehicle personnel for the payloads, is equivalent to 0.0058-in. displacement of the center of gravity from the spin axis for a 21.5-lb payload. The calculated method gives an equivalent center-of-gravity displacement due to static imbalance of 0.0005 inch, while the graphic method results in 0.0004 inch. Both results are better than specifications by a factor of ten.

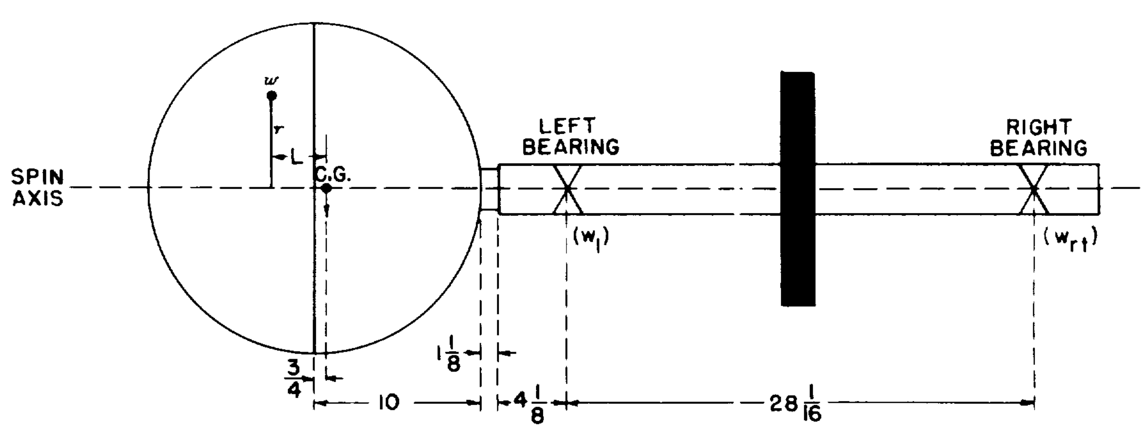



Figure B1 - Typical dimensional relationship for 20-inch-diameter satellites

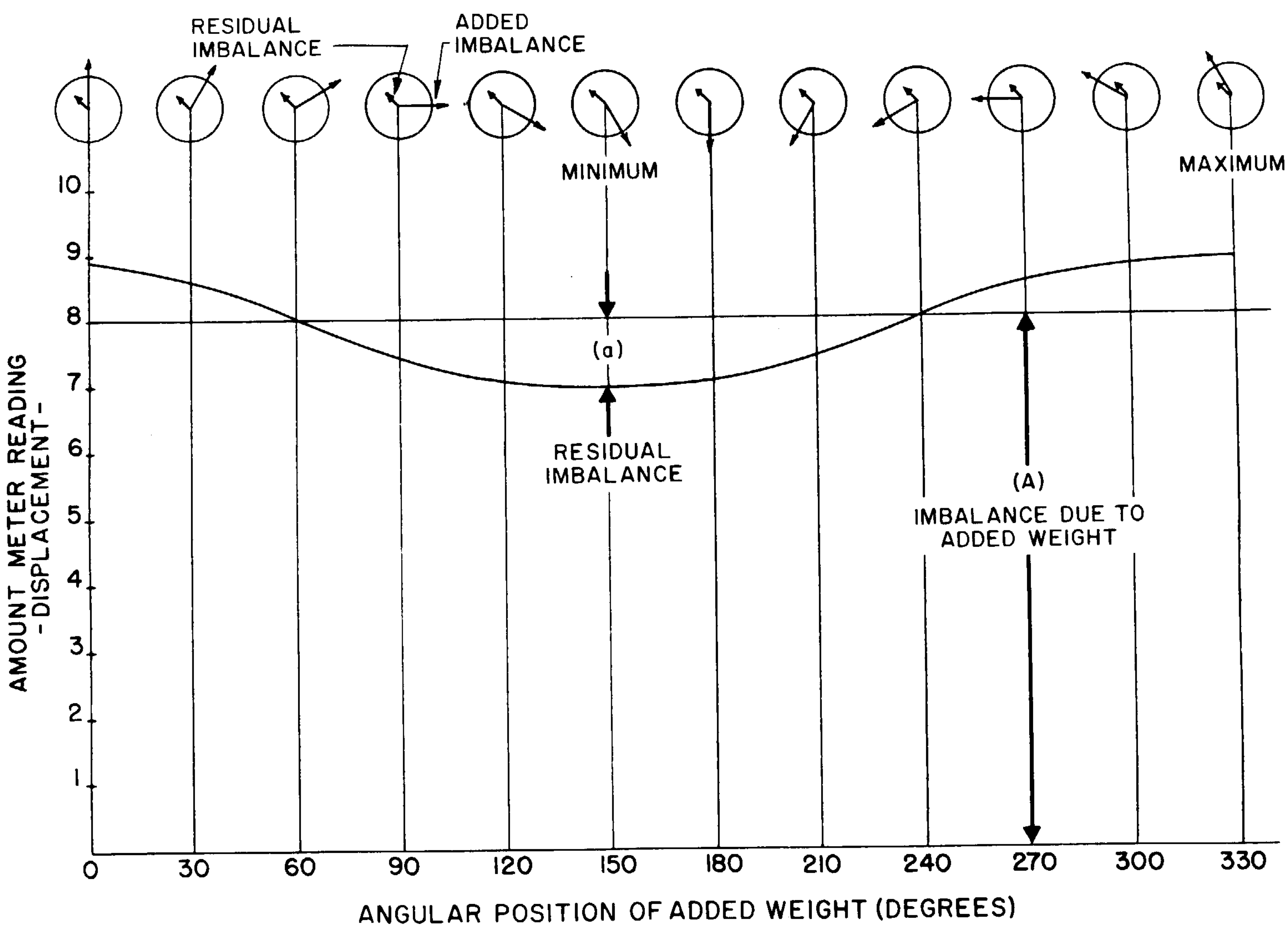



Figure B2 - Relation between real and imaginary weights

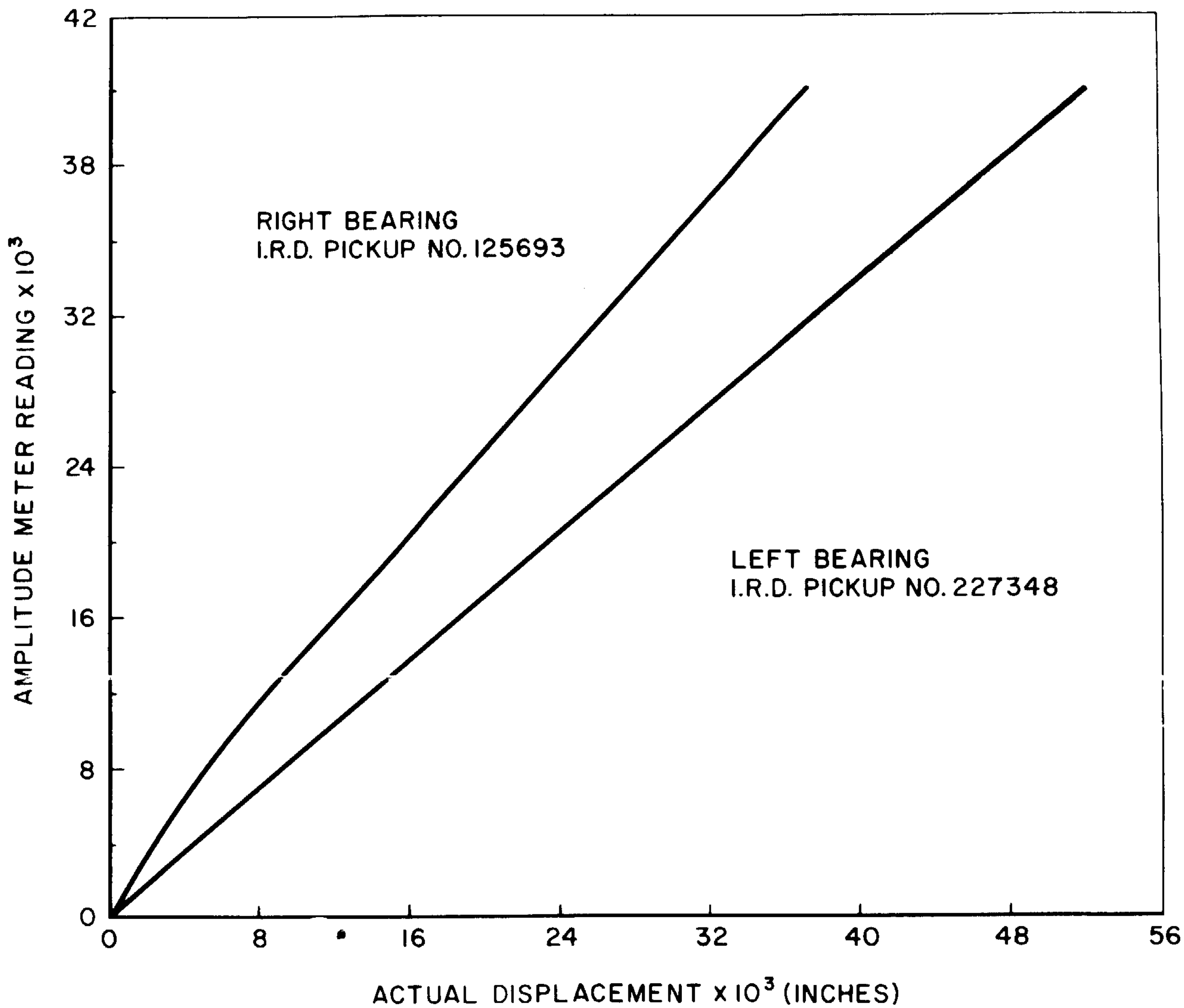
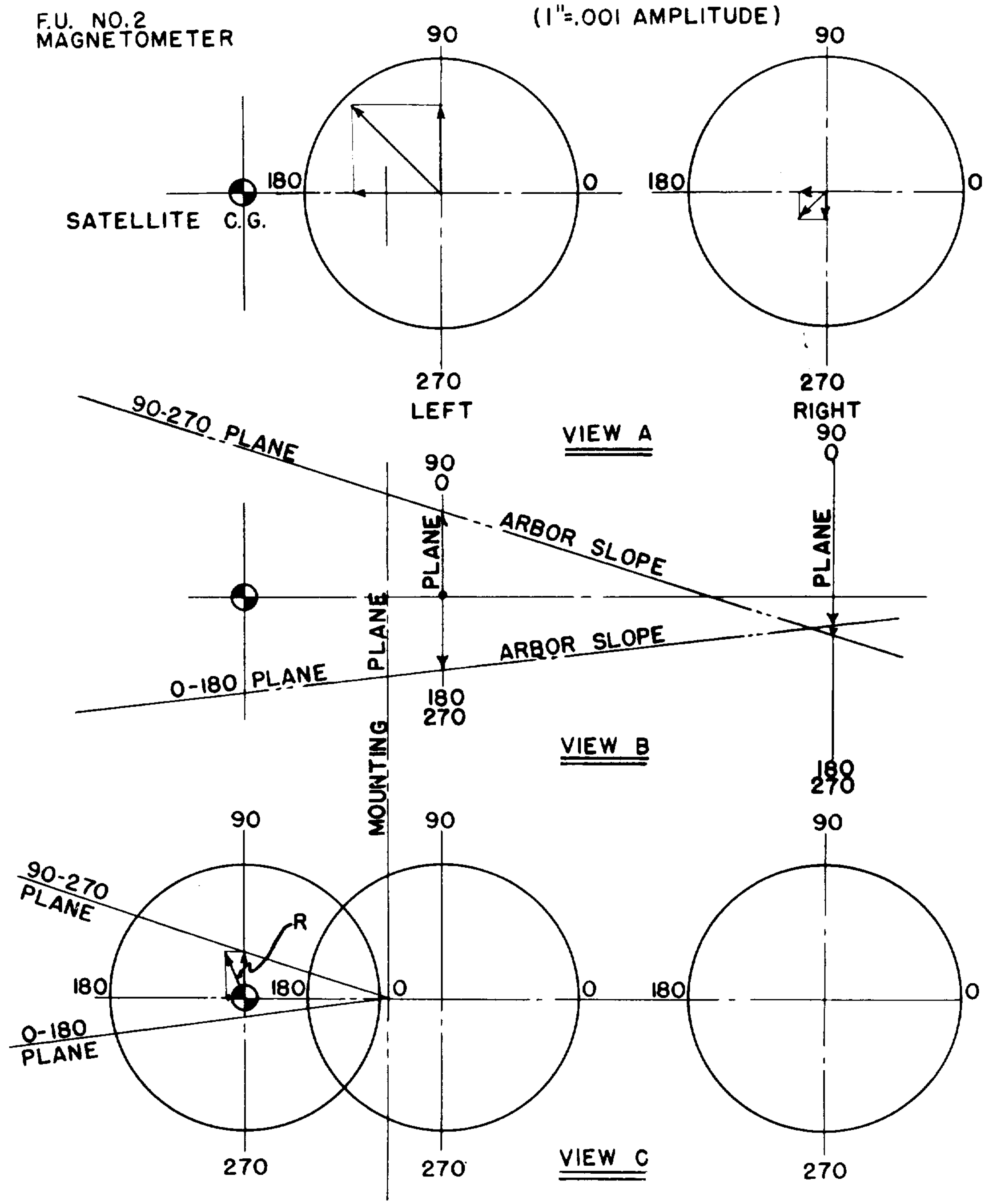



Figure B3 - Calibration curves for low-frequency vibration pickups




$R \times W_S$ = EQUIV. STATIC IMBALANCE
0.00038 X 20.52 LB = 0.0078 IN.-LB
= 0.124 OZ-IN. (EQUIV. STATIC IMBALANCE)

Figure B4 - Graphical determination of center-of-gravity displacement

## Appendix C

## SURVEY OF BALANCING EQUIPMENT

A list of manufacturers of balancing equipment was obtained from the 1958 Thomas Register, and letters were sent requesting all available information on balancing equipment.

Literature received from the manufacturers was used as the source of information for the accompanying table. The tabulated data give the range covered by the entire line of machines manufactured by the company, for example, the maximum swing diameter for American Trebel is 8 to 120 inches, which includes several sizes of machines. All figures given are for standard equipment. However, certain companies — notably Gisholt, Tinius Olsen, and American Trebel — indicate they are willing to adapt their machines to customer's specifications.

After a thorough review of the literature, it appears that the equipment of American Trebel, Gisholt, and possibly Tinius Olsen closely fits the requirements for the proposed applications. A Gisholt representative stated that their machines could be altered to accommodate a maximum swing of 90 inches at 200 rpm. The literature for American Trebel indicates their maximum standard swing is 120 inches; however, the exact speed is not known.

A fourth company, Stewart Warner, utilizes a unique method of balancing: revolving the workpiece to a point beyond the resonant frequency and allowing the workpiece to coast back through this frequency while noting the amplitude and phase readings for this particular frequency. This is mentioned here because of its remarkably wide weight range. One machine listed by the company is capable of handling weights between 1 and 5000 pounds with a sensitivity of 0.04 ounce-inch. This characteristic is not available, apparently, in other machines.

Table C1 - Manufacturers' data on balancing machines

| Company | Weight range of work (lb) | Swing diameter (in.) | Bearing separation (in.) | Sensitivity | Speed (rpm) | Method of vibration detection |
|---|---|---|---|---|---|---|
| **Horizontal dynamic** | | | | | | |
| American Trebel[c] | 0.1 - 220,000 | 8 - 120 | 10-234 | 0.000025-0.0002 | 140- | Coil-magnet |
| | | | | 0.000008 special | | |
| Annis[b] | 0.03 - 400 | 3 - 18 | 3-36 | 0.000020 | 600-15,000 | Photoelectric |
| Bear Mfg.[c] | 0.3 - (as specified) | 5 - 84 | 8-60 | | 265-4600 | Spark-indicator |
| Gisholt[c,b] | 0.2 - 10,000 | 6 - 68 | 6-72 | 0.000025 | 300-3000 | Coil-magnet |
| Globe Tool[c] | 0.1 - 25,000 | 9 - 120 | 15-120 | 0.001-1.6 oz-in. | 0-600 | |
| | | | | 0.002-48 oz-in.$^2$ | | |
| IRD[b] | 5 - 5,000 | 60-72 | 78-110 | 0.000025-0.000150 | | Coil-magnet |
| Micro-Balancing[b] | 0.1 - 600 | 1-1/8 - 37 | 1-47 | 0.0000002-0.00001 | 600-24,000 | Magnetic |
| Raydyne[b] | | | | | | Seismic |
| Rava[c,b] | | | | | | |
| Stewart-Warner[b] | 0.3 - 5,000 | 1-1/4 - 68 | 4-1/4-83 | 0.004-0.04 oz-in. | above resonant | Coil-magnet |
| Tinius-Olsen[c] | 0.2 - 3,000 | 4 - 60 | 10-84 | 0.0005-0.18 oz-in. | | Coil-magnet |
| | | | | 0.000010-0.000125 | | |
| Vib. Specialty[b] | 0.2 - 150,000 | | | 0.2-1 oz-in. | | Mechanical lever system |
| **Vertical dynamic (two-plane)** | | | | | | |
| American Trebel | | | | | | |
| Tinius Olsen | | | | | | |
| Gisholt | 1 - 50 | 11-1/2-17-1/2 | | 0.000050 | 1000-2000 | Coil-magnet |
| **Vertical static (one-plane)** | | | | | | |
| American Trebel | 0.5 - 880 | | | | 500-1800 | |
| Gisholt | 1-50 | 11-1/2 to 17-1/2 | | 0.000050 | 1000-2000 | |
| Micro-Poise | ?-4000 | | | | | |
| Rava | 0.3-22(?) | 23-1/2 | | 0.000020 | 900-3600 | |
| Taylor | 30-1000 | 12-50 | | | | |
| Tinius Olsen | 50-400 | 16-40 | | 0.000012-0.000025 | | |

[b]Data obtained from brochure.
[c]Data obtained from catalog.