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APPLIED RESEARCH & DEVELOPMENT ON TRIAXIAL PIEZOELECTRIC
(PZL) ACCELEROMETER SYSTEMS OF IMPROVED DESIGN

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August 1977

Final Report for period 75 December to 77 July

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interference due to body motion acceleration. Other improvements were made to simplify the system. A radar transponder was added to assist in tracking the payload which required re-integration of the total system.

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FOREWORD

This document is the Final Report required under AFGL Contract F19628-76-C-0129 describing the contract effort to evolve falling-sphere systems for the measurement of high altitude atmospheric density. This effort extended and refined that done under Contract F19628-73-C-0112.

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NOMENCLATURE

a	= Acceleration
d	= Distance, diameter, inches
e	= Base, natural logarithm
I	= Moment of inertia, lb-in-sec ²
K	= Constant of proportionality
M	= Mass, Kg, slugs
t	= Time, seconds
T	= Torque, lb-ft, N-M
W	= Work, ft-lbs, ergs
ω	= Frequency, angular velocity, radians/second
ω_n	= Natural frequency, radians/second
θ	= Angle in radians or degrees

I. INTRODUCTION

The object of the effort under this program was to further develop the AFGL piezo-electric falling-sphere atmospheric density measuring system reported in Documents AFCRL-72-0033, AFCRL-TR-74-0123, and AFGL-TR-76-0064, and to fabricate and provide field services for four falling-sphere systems. Considerable effort was expended in data analysis after each mission to obtain system-improvement information to feed forward into future development efforts.

To enable the tracking radar to differentiate between the payload and the various debris that occurs at separation, the sphere was provided with a C-band transponder or beacon. This required the repositioning of the various sub-systems within the sphere to provide the additional volume required for this package while at the same time maintaining static balance and spin-stability without the addition of excessive trim-ballast mass.

The slight unavoidable eccentricity of the sphere separation system causes a small transverse impulse which perturbs the sphere causing undesired nutational-acceleration noise in the high-sensitivity channels. This interference appeared in the Z channels and was eliminated by the use of the same notch filter system that was used in the X and Y channels, and was reported in AFGL-TR-76-0064.

II. SYSTEM IMPROVEMENTS

2.1 General

As a result of continued studies of the system, and in particular as a result of flight data analysis, a continuing program of system refinement has been maintained. The salient improvements are enlarged upon below. In addition, improvements have been made in packaging such as changes in the mounting technique of the electronics into the accelerometer, and in the accelerometer package itself to facilitate fabrication. A general program for the upgrading of the electronics has continued with this contract, as in the past, to keep abreast of the state-of-the-art in components, particularly in the semi-conductor field.

2.2 Improved Analog-output Limiting

The thirteen analog outputs of the system require limiting at levels slightly below -5 volts and slightly above +5 volts to prevent the over-driving of the commutator system. To accomplish this task the former design included two back-to-back zener diodes across each output with each having a limit-rating of approximately 5.1 volts. Thus, a total of 26 diodes were required for each system. It was determined that the same limiting action could be achieved without impairment to amplifier linearity by the use of a lowered supply voltage to the amplifiers. This change in addition to the elimination of the 26 diodes, reduces component stressing and power dissipation.

2.3 Filtering

Because of nutational acceleration interference, notch filters were added to the X and Y spin-plane axes after the Aladdin program in 1974. It was felt that since the Z-axis was parallel to the spin axis, nutational acceleration interference would be negligible and because of this, added to the interest in maintaining a flat Z-axis low-frequency response, notch filtering was omitted from Z-axis channel. Subsequent flight testing proved that filtering is required in all three channels X, Y, and Z and, hence, a twin-T filter was incorporated into the Z-axis amplifier chain. These filters have an insertion loss at the nutational frequency of the order of 100db and have proven to reject nutational acceleration to levels that are well below the threshold level of the accelerometer.

2.4 Signal Distortion Considerations

The notch filter modified the low frequency response of the Z-axis channel by decreasing the roll-off frequency at the low ends thereby improving the low frequency response near zero frequency. It necessarily places an anti-resonant cusp at the nutation frequency of 0.9 Hz. As a result of this latter modification there exists the possibility that the acceleration time function is affected resulting in a measurement error. Analysis was initiated under this contract to determine if there exists significant distortion in this channel. This work is continuing as in-house effort at AFGL.

In the event that significant Z-axis distortion exists, a simple closed-loop compensation circuit has been designed to be used as part of the post-flight data reduction system in the laboratory. This circuit will compare the analog flight data with the output of a flight-type Z-axis amplifier chain by the use of a high-gain differential amplifier. The output of this amplifier will be fed back to the Z-axis amplifier input which will, in turn, drive the Z-axis amplifier output to match the analog flight data to within a small insignificant difference. The Z-axis input signal will then be the true analog of acceleration as it occurred in flight. This signal will then be encoded and taped for use in the usual data reduction process. This design was turned over to AFGL/LKB for implementation as an in-house effort.

III. SPHERE INTEGRATION

3.1 Beacon Integration

To facilitate radar tracking of the sphere in the presence of nose-cone segments and other debris resulting from the sphere separation from the rocket, a radar transponder or beacon was incorporated into the payload system. Because of the volume and form-factor of this package a general re-integration of the system had to be undertaken.

As pointed out in earlier reports there exist several constraints in the placement of the subsystem packages into the sphere:

1. The accelerometer sensing center must be at the sphere center of mass.
2. The center of mass must be at the geometrical center of the sphere.
3. The moment of inertia must be that of a spin-stable homogeneous oblate spheroid having an inertia ratio of approximately 1.15.
4. Ease of cabling, and the heat-sinking of the transmitter package must be considered.
5. The above constraints must be met with the addition of minimal trim ballast.

Preliminary configurations were made in sketch form and constraints 1 and 2 were checked by writing equations for 1st and 2nd moments. The best paper design was then implemented in hardware form and optimization of the configuration was then made by shifting the cells of the battery to strategic positions.

The final design required the addition of two auxiliary decks shown in Figures 1 and 2 upon which the DC-DC converters were placed along with one nickel-cadmium cell. The beacon was placed under the main deck in the general area formerly occupied by the converters, as shown in Figure 3. Additionally, one cell was placed in this area to provide necessary trim mass. The remaining cells, 20 in number, are placed on the top of the main deck as shown in the figures.

3.2 Beacon Antenna Change

The C-band beacon antenna is a separate system having a separate connector potted into the plastic antenna band along with the S-band antenna. Care had to be

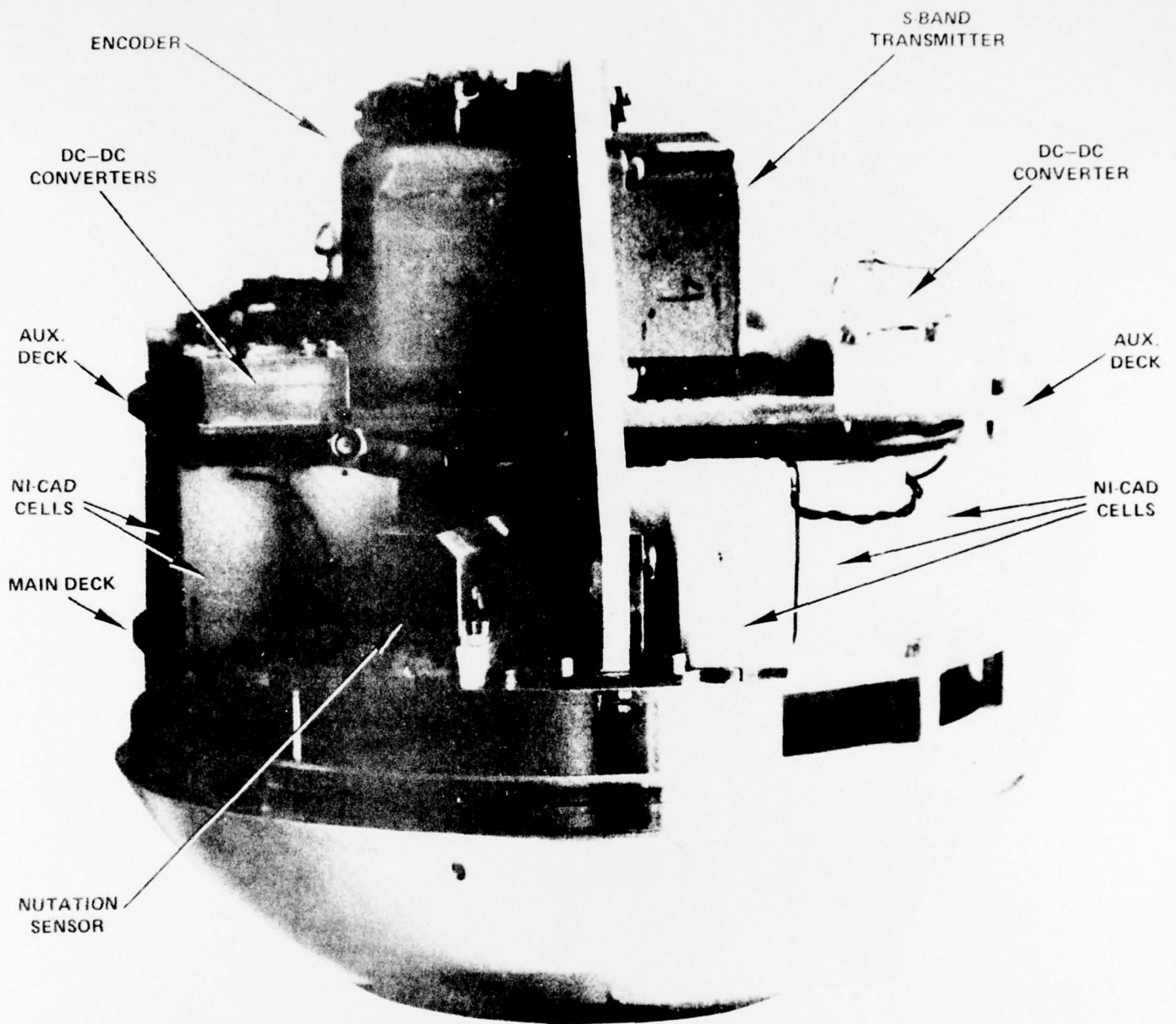


Fig. 1
Side View Ten-Inch Sphere

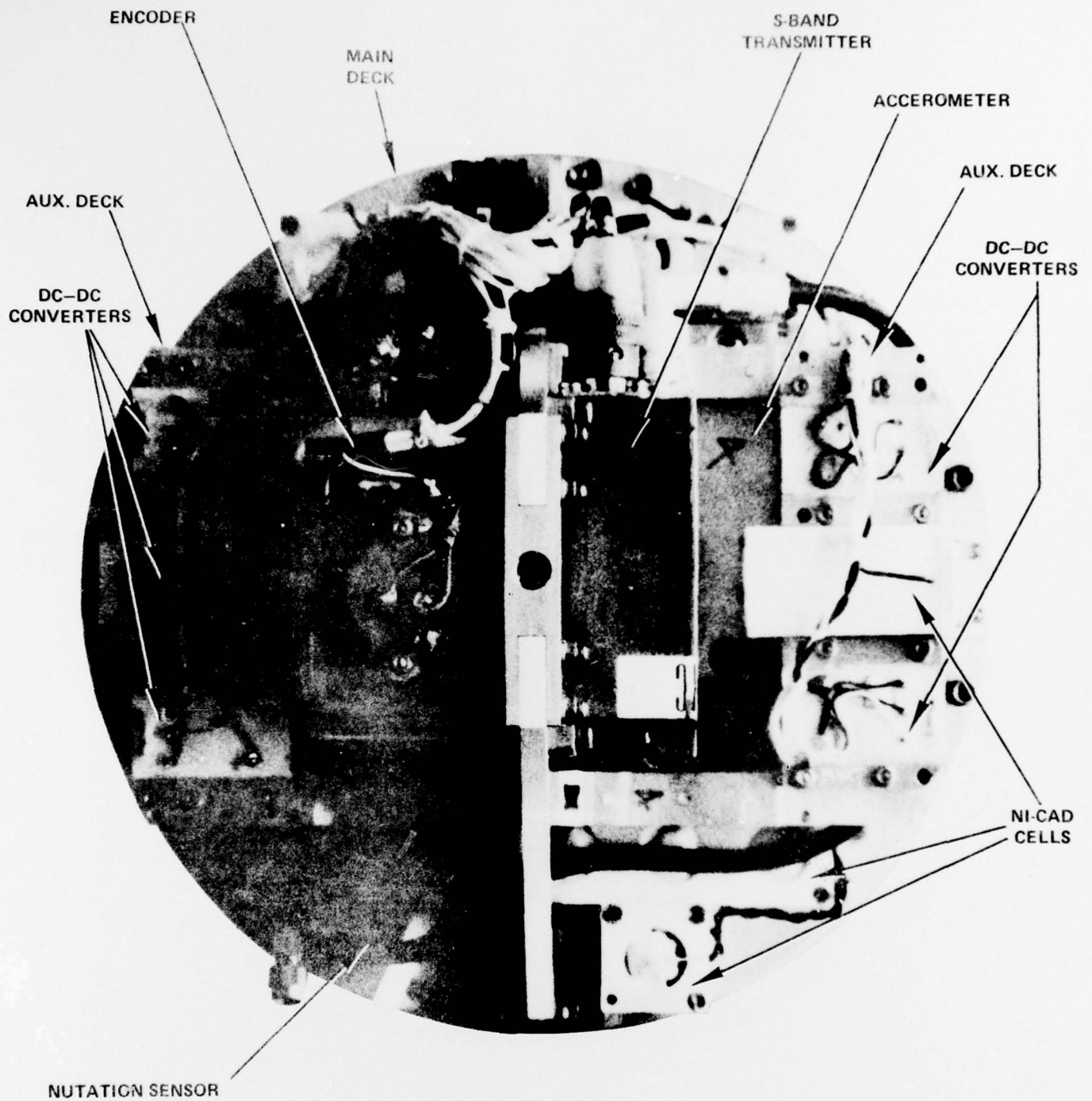


Fig. 2
Top View Ten-Inch Sphere

RADAR
BEACON

POWER
CONTROL
UNIT

MAIN
DECK

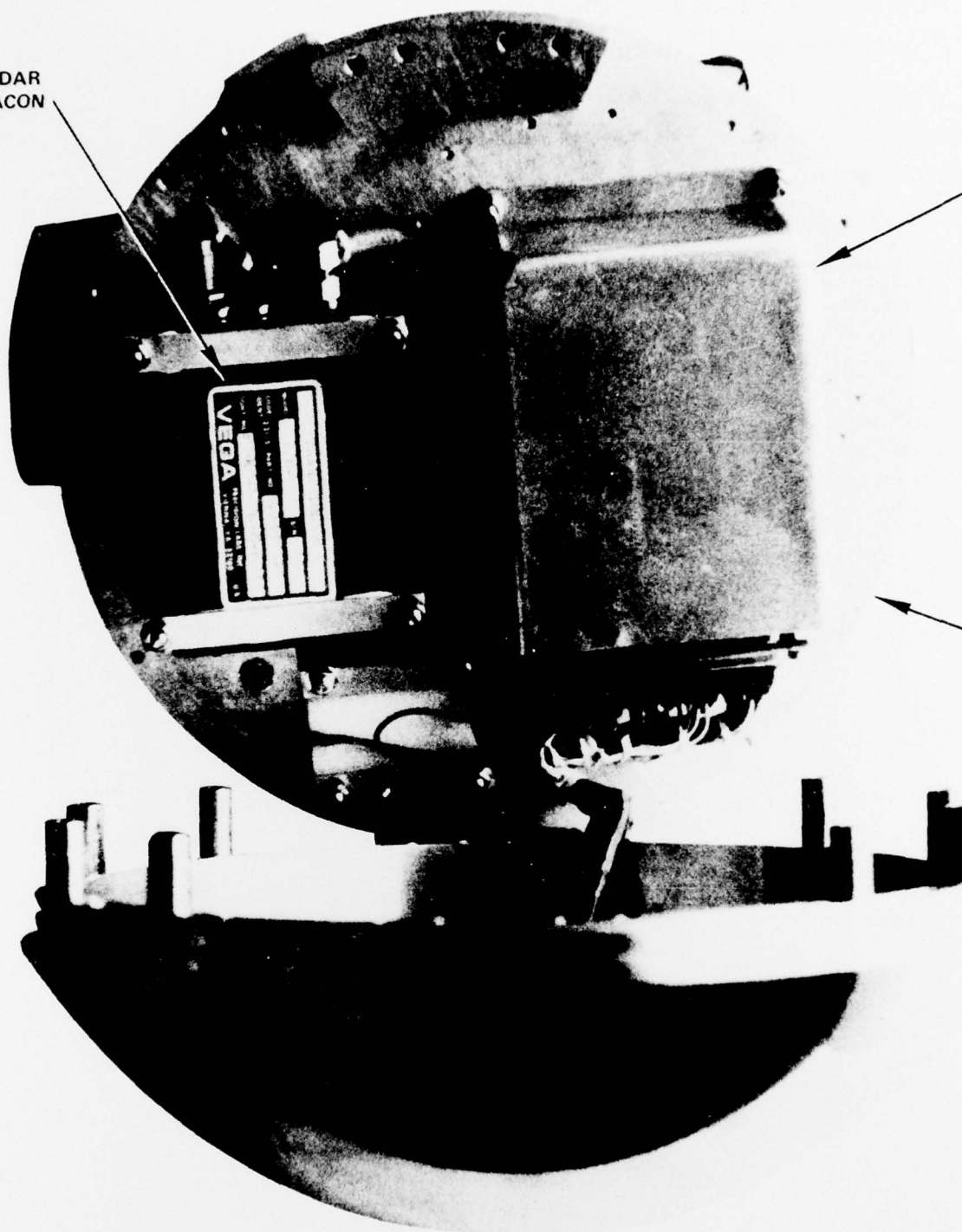


Fig. 3
Bottom View Main Deck Ten-Inch Sphere

taken in the integration task to allow room for the beacon connector which juts radially into the payload inner volume, and to allow room for the coaxial-cable bend radii. Consideration for the transmitter connector and cable compounds this problem. The beacon antenna feed point was changed by AFGL after the initial integration and fabrication of one beacon-equipped sphere. This impacted the integration by requiring the re-positioning of cells and main wiring cable to allow for the re-routing of the beacon coaxial cable. Because the new feed-point position of the beacon antenna placed the antenna mass in a more balanced position the trim ballast mass could be reduced.

IV. SPHERE FABRICATION

Four accelerometer systems and nutation sensors along with four sets of the required decks, bracketry, and mounting hardware were fabricated. This hardware, along with the GFE provided by AFGL, was integrated into the four spheres required under this contract. These items were numbered AC-3 through AC-6. Serial numbers AC-4 through AC-6 contained radar beacons, AC-6 used the new beacon antenna configuration, and all four included the Z-axis notch filter.

The sphere weights were as follows:

AC-3 20.75 lbs.

AC-4 22.31

AC-5 22.31

AC-6 21.64

The increase in weight from AC-3 to AC-4 reflects the addition of the beacon with its cable and antenna. The decrease in weight from AC-5 to AC-6 reflects the beacon antenna configuration change.

V. FLIGHT TESTING

Field services were provided for the four payloads which were flown in three rocket programs:

SPHERE NO.	LOCATION	DATE
AC-3	Fairbanks, Alaska	February 1976
AC-4 AC-5	Kwajalein, M.I.	August 1976
AC-6	Kwajalein, M.I.	May 1977

The performance of all payloads that achieved design altitude was satisfactory and useful scientific data were obtained. During the first Kwajalein mission one sphere, AC-5, was lost due to ignition failure in the second-stage rocket. The sphere separated and uncaged as programmed but did not achieve sufficient altitude to yield useful data. The Y-axis of sphere number AC-4 became inactive between launch and separation and did not yield Y-axis data. However, since the X and Y axes are redundant, sufficient data were obtained from the X-axis to provide satisfactory results for this mission.

VI. DATA ANALYSIS

The flight records for each flight were analyzed to ascertain the performance of the rocket, separation system, caging system, and accelerometer system. Anomalous performance is noted and their causes are studied to obtain design improvement information to feed forward into follow-on systems. These studies, of necessity, overlap into the scientific data analysis effort, especially in the area of techniques as affected by vehicle dynamics.

6.1 Y-Axis Failure, AC-4

The failure of the Y-axis during the August 1976 mission has been investigated to determine its cause. The following observations were made from flight record studies:

1. The Y-axis channels were operative during pre-launch check-out and during the launch phase.
2. The Y-axis channels were inoperative after separation.
3. All other channels and systems were electrically normal for the flight.
4. At approximately 390 seconds after lift-off a burst of signal was observed in the Y-3 channel. This signal was modulated at the spin rate and, therefore, appeared to be the result of an externally applied acceleration pulse.
5. All Y-axis channels were at zero or mid-band except during Observation 4.

From these observations the following conclusions can be made:

1. The area of malfunction had to be confined to the Y-axis transducer, amplifier chain, and its DC-DC converter.
2. The transducer bimorph did not fracture because the Z axis functioned normally. A fractured Y-axis bimorph would cause its mass load to mechanically interfere with the adjacently-located Z-axis transducer and cause spiking in the Z-axis output.
3. A bimorph lead did not part because a burst of acceleration signal was observed late in the flight.
4. The amplifiers which are cascaded to provide the four acceleration ranges did not fail because the outputs of the Y-axis were at their normal

zeros. Failure of any amplifier in a chain results in a 5 volt off-set (band edge) either negative or positive.

5. It has been observed in the laboratory that a strong signal will couple through a powered-down chain to outputs 3 and 4 due to passive diode coupling. The signal observed in channel Y-3, Observation 4 above, could have been diode coupled.
6. The foregoing indicates a failure of the Y-axis DC-DC converter just prior to, or immediately after separation.

The DC-DC converters used for each accelerometer channel and the nutation sensor are MIL-spec units and have been used reliably in many satellite and rocket payloads. This fact notwithstanding, these units are now being tested and burned-in under a more stringent procedure.

6.2 Degraded Up-Leg Data

Theoretically, it is possible to obtain a satisfactory density profile by using either the upleg or downleg portion of data acquired during the sphere trajectory. The use of both portions is desirable because two related measurements are obtained that are separated temporally and spatially by relatively small increments. However, because of the danger of the sphere colliding with nose cone segments and other smaller pieces of hardware immediately after payload separation, sphere ejection has been programmed to occur near 70 km. In addition, several seconds are needed after ejection for the uncaging of the accelerometer and for decay time of the shock induced ringing of the transducers. Thus, the upleg measuring interval is shortened as compared to the downleg because of these imposed conditions.

It was noted that the accelerometers on sphere AC-4 experienced excessive ringing as compared to the other flights and further shortened the up-leg data interval. It appeared that the uncaging shock was much higher than is normally experienced. Experiments in the laboratory, using the flight squib-driver circuit proved that the DM2535* dimple motor squibs used in the design occasionally burst with explosive force. However the driver circuit appeared to meet performance requirements when checked against the manufacturers specifications for the DM25J5 squib. A call to

*Herules Powder Co.

the manufacturer revealed that this problem had arisen in other systems where firing energy is high. If the firing energy is excessive the residue of the powder charge, after initial firing, provides a path for a heavy current to flow which vaporizes the residue and adjacent metal causing a rapid pressure rise within the sealed case resulting in an explosive rupture.

The present squib driver is simply a relay that switches the full battery voltage across the squibs for a period of two seconds involving a very high energy level. The manufacturers recommendation for firing the DM25J5 is a capacitor-dump circuit where the energy is limited to 7500 ergs. This technique will be designed into a new firing circuit which will be used in follow-on systems.

6.3 Anomalous Data, Sphere No. AC-4

Anomalies were observed in the air-drag data, obtained from the August 1976 mission using sphere no. AC-4 (Kwajalein) starting at 384 seconds of flight, or at approximately 70 km of altitude on the down-leg. This was in the form of a 4.5 second burst of periodic acceleration occurring at 384.5 seconds superimposed on the normal Z-axis drag acceleration, a burst of second harmonic distortion on the Y-axis record occurring at the same time, and an apparent vehicle aspect change of 5-6 degrees occurring at 384 seconds which caused an erroneous departure in a drag acceleration measurements for the remainder of the flight.

Radar tracking data obtained from the mission revealed considerable debris re-entering along with the sphere. These data indicated that a large piece, possibly one of the clam-shell halves, passed within six to thirty meters of the sphere at an altitude of 70-80 km. This suggested that the sphere may have been struck by smaller pieces of debris and may have been translated and torqued by wake turbulence from the larger piece. This led to the re-inspection of the acceleration records for the mission and the following was observed:

1. There was no evidence of the spiking that would be expected as the result of collisions with debris. Thus it is unlikely that collision occurred.
2. Spin axis quadrature torquing was evident at 384-385 seconds of flight as indicated by the second harmonic distortion of a duration of approximately one second occurring in the Y-axis data.

3. A nearly periodic linear acceleration was measured in the direction of the spin axis (Z-axis) having a peak value of $8 \times 10^{-2}g$, at a frequency of approximately 4.5 Hz, occurring in the interval 384.5 to 390 seconds of flight.

Observations 2 and 3 were closely corroborated by the data reported in the XONICS Letter No. 893 of 27 April 1977. These data showed nearly periodic changes at approximately 4.5 Hz in doppler velocity in the interval 383 to 390 seconds of flight. The peak amplitude of the velocity change was approximately 0.025m/s. This yields a dynamic acceleration of

$$a = \frac{\Delta V}{\Delta t} = \frac{\Delta V}{1/4F}$$
$$= \frac{0.025}{1/4 \times 4.5} = 0.45 \text{ m/s} = 4.6 \times 10^{-2} g.$$

which is of the same order as measured by the Z-axis sensor of the accelerometer. This appeared to be a rapid bouncing of the sphere possibly caused by the linear wave motion of the wake from the large piece of debris.

The energy involved in this linear perturbation is estimated by

$$W = \frac{1}{2}MV^2 \text{ from which}$$

$$\Delta W = MV\Delta V$$

For the 20-lb sphere $M = 0.62$ slugs. The velocity at 384 seconds was approximately 1.65 km/sec or 5413 ft/sec. From the XONIC data $V = 0.025$ m/sec or 0.082 ft/sec giving:

$$\begin{aligned}\Delta W &= 0.62 \times 5413 \times 0.082 \\ &= 275.7 \text{ ft-lbs} \\ &= 3.7 \times 10^9 \text{ ergs}\end{aligned}$$

In addition to linear wave motion it is reasonable to expect that a considerable amount of energy in vortex motion, or curl, existed in the wake of the debris. Consider the quadrature torque required to precess a spinning body

$$\tau = I \omega \frac{d\theta}{d\tau} \quad \text{where}$$

ω is the spin and θ is the angle of precession. The energy involved in torquing the body through $\Delta\theta$ is given by

$$\Delta W = I \omega \frac{(\Delta\theta)^2}{\Delta t}$$

The moment of inertia I of the sphere is $0.3574 \text{ lb-in-sec}^2$. Assume that the sphere spinning at 5 Hz is torqued through a $\Delta\theta$ of 0.1 radian (5.73 degrees) and, because of the lowered relative velocity, this occurs in one second:

$$\begin{aligned} \Delta W &= 0.3574 \times 2\pi 5 \times (0.1)^2 \\ &= 0.112 \text{ in-lbs} = 0.009 \text{ ft-lbs} \\ &= 1.27 \times 10^5 \text{ ergs.} \end{aligned}$$

This vortex energy is four orders of magnitude lower than the translational energy calculated above and, hence, it appears reasonable to expect that a torquing of the sphere, of at least 5-6 degrees, resulted from viscous coupling of a vortex component in the debris wake that passed over the sphere.

In conclusion, the foregoing suggested that the wake of a large piece of debris (half of the clamshell or the second stage) passed the sphere during the time interval 384.5 to 390 seconds in the flight corresponding to 70 to 60 km of altitude. The pass was close enough to cause translational acceleration or bouncing of approximately $\pm 5 \times 10^{-2} \text{ gs}$ and involved energy of the order of 10^9 ergs . From this it seems reasonable that the wake contained vortex energy of the amount 10^5 ergs , or the amount required to cause the 5.6 degrees of aspect rotation.

VII. CONCLUSIONS

Overall, the effort expended in the performance of this contract has been fruitful in that useful scientific data were obtained from each successful launch. In addition, each flight produced technical information that suggested refinements to the system, some of which were implemented as described above. It is recommended that the following refinements and studies be included in the follow-on effort:

1. Analysis of the Z-axis amplifier response to determine response to an exponential time function closely approximating the actual flight acceleration function, and the fabrication of a special function generator to enable laboratory verification of the analytic results.
2. The fabrication of the Z-axis data compensator described above in paragraph 2.4.
3. The implementation of the capacitor-dump squib driver circuit described above in paragraph 6.2.