METEOROID MEASUREMENTS
WITH PROJECT PEGASUS

by

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Introduction

The prime objective of Project Pegasus is to measure, in the vicinity of the earth, the meteoroid penetration frequency in aluminum sheets of thicknesses which approach those of space capsule walls. Plans for the project were initiated at NASA in 1962 by the Office of Advanced Research and Technology and the George C. Marshall Space Flight Center. Throughout the project, members of the Langley Research Center supported the project with experiments and advice.

Knowledge of the abundance of penetrating meteoroids in the near-earth space is an indispensable requirement for the designer of spacecraft. For him, the velocities, directions, and masses of meteoroids are of secondary interest only; the question of how many meteoroid punctures occur in a sheet of given area, thickness, and material during a given period of time has primary significance. Project Pegasus was initiated to answer that question.

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Spacecraft Design

In 1962, existing knowledge of meteoroid abundance in the vicinity of the earth was quite limited. Rocket and satellite measurements had provided some data for meteoroids between about 10^{-12} and 10^{-7} g. At the other end of the spectrum, optical and radar observations had furnished abundance data for meteoroids above about 10^{-4}g. The mass region between 10^{-4} g and 10^{-7} g was free from data points. This region, however, is most important for the spacecraft designer since it contains meteoroids which, because of their size and abundance, are of potential danger to spacecraft.

An experiment to collect puncture data for meteoroids above about 10^{-7} g would have to be designed in such a way that a maximum sensitive area, hopefully more than 100 square meters, could be exposed. Rough calculations showed that a total area of about 200 m^2 of a lightweight sensor could be carried on a Saturn I-launched satellite. During a useful lifetime of one year, 50 to 100 meteoroid punctures through an aluminum sheet of about half a millimeter thickness could be expected according to interpolated abundance data available at that time.

Early in 1963, a contract was let to the Fairchild Stratos Corporation, later re-named the Fairchild-Hiller Corporation, to develop a meteoroid-measuring satellite as illustrated in Figure 1. It carries sensors on both sides of its wing-like structures; the areas of the sensors, and the thicknesses and materials of the target sheets, are listed in Table I.

The satellite was carried within the space available in the boilerplate model Apollo Service Module and Service Module Adapter. After the orbit had been established, Service Module and Command Module were ejected; the Pegasus spacecraft remained attached to the Service Module Adapter, the Instrument Unit, and the depleted SIV stage (Figure 2). One minute after ejection, the wings were deployed by combined spring and motor action.

Electronic System

A schematic drawing of the six major subsystems of the Pegasus electronic system is shown in Figure 3. These six subsystems are the meteoroid detector subsystem; the attitude sensing subsystem; the temperature subsystem; the data subsystem; the communications subsystem; and the power subsystem. Power is derived from an array of solar cells which are mounted on four panels oriented like the four sides of a tetrahedron. Each panel is capable of providing the full power needed by the system at a peak voltage of 45 volts and a current of 2.85 amps (Figure 4).

The data system employs low speed circuits to control data flow, and to digitize, process, and store all primary data on meteoroid hits, and some of the housekeeping data. Two telemetry links are employed to transmit data to earth: the main telemetry channel, and the beacon channel (Figure 5). The main channel transmits, upon ground command, all data which have been stored in the memory; these are the meteoroid puncture data, radiation data, attitude data, meteoroid sensor temperatures, and temperatures of four samples of thermal coating. Besides being stored in the memory and read-out on command, these data are also transmitted in real time through the beacon telemeter, along with a set of 90 yes-no type data on equipment status, and 58 analog channels. The analog data frequency modulates a 730-cps subcarrier oscillator.

The data contain information on voltages, currents, temperatures, and meteoroid hits, in addition to the measurements which are stored in the memory. The beacon signal is also used for acquisition and tracking of the satellite. Figure 6 shows further details of the data transmission system. For all major functions, the systems provide two redundant units which can be selected by ground command. The communications subsystem contains two beacons for PAM and PCM transmission and two command-operated FM transmitters for the stored PCM data.

Temperature Subsystem

The temperature subsystem comprises three classes of measurements: temperatures of electronic components within the canister; temperatures of the meteoroid sensor panels; and temperatures of four selected samples of thermal coatings. Early in the thermal analysis of the Pegasus design, it was realized that it would not be possible to maintain the temperatures inside the electronic canister within design limits by passive means alone, such as coatings, insulation layers, and finishes. It was necessary to apply an active louver system, controlled by temperature-sensitive bimetallic strips. The louvers face the top end of the empty SIV stage which, by virtue of its size and a specially developed, highly reflective paint, maintains a fairly constant low temperature of about 265° K. In this way, it is possible to maintain a temperature between 275° K and 330° K for the components within the canister (Table II). The desired temperature range of the meteoroid sensor panels was obtained by coating the panels with a chemical conversion layer (Alodine, MTL3) which has a ratio of solar absorptance to infrared emittance of about 1.0. Figure 7 shows sample results of temperature measurements on meteoroid sensor panels.

Radiation Sensor

Shortly after Project Pegasus had been initiated, studies at the Langley Research Center and at other places on the entrapment and subsequent release of electrons in a dielectric which was exposed to a high dose of electron radiation pointed to a potentially serious problem in connection with the capacitor-type meteoroid sensors on Pegasus. The electronic discharges produced pulses which were not unlike those pulses which were generated by meteoroid punctures. Although an electronic discriminator was designed and used to eliminate all radiation-induced pulses from the meteoroid puncture data channel, it still appeared desirable to measure the radiation dose onboard the Pegasus vehicle. The radiation sensor consists of a scintillator crystal with photomultiplier tube and data processing equipment which sorts out electrons between 0.5 and 11 MeV, and 2 and 11 MeV.[†] Careful evaluation of the radiation data and the meteoroid puncture data on the Pegasus flights did not reveal any potential false meteoroid counts because of electron radiation-induced pulses. However, the radiation experiment in itself turned out to be a very interesting and valuable study of the South Atlantic magnetic anomaly, which causes the Van Allen Belts to reach down to relatively low altitudes in this region. Figure 8 shows the radiation count during several orbits which pass through the anomaly. Figure 9 gives a plot of the radiation intensity. The count rises from 100 per second outside the anomaly to 10^7 per second within the anomaly.

Attitude Determination

It had been expected that the Pegasus satellites would assume a slow spinning and tumbling motion in space generated by slightly

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[†] On Pegasus III, the lower energy threshold was 0.1 MeV.

unsymmetrical venting of unburned hydrogen through two radial vent pipes. This motion is desirable because it provides a variation of the satellite orientation as a function of time. Knowledge of this motion is essential for an analysis of the directionality of meteoroids in space. The information necessary for the determination of satellite attitude is provided by a set of 12 earth sensors, and a set of 5 sun sensors. Each earth sensor contains a little pile of thermo-elements, and a germanium lens; this system responds to the infrared radiation from the earth. One pair of sensors is mounted in such a way that the sensors face in opposite directions; the 12 sensors are oriented along the twelve face normals of a dodecahedron. A sensor pair produces no difference signal when both sensors look at space. When one sensor looks at the earth, a difference signal is generated. By analyzing the outputs of the 6 sensor pairs, the direction of the satellite-earth line can be established within a few degrees. The direction of the satellite-sun line is obtained from 5 sun sensors. Each sun sensor consists of an array of strip-shaped photocells and a system of slits perpendicular to the cell strips which are masked in a specific pattern. This array produces a digitized output from which the direction of the sun can be determined. When the direction of the earth and the direction of the sun are known, both with reference to a satellite-fixed coordinate system, and when the location of the satellite is known, the attitude of the satellite can be derived. Pegasus I began with a spin of about 10° $\sec^{-1}$ around its longitudinal axis, which is also its axis of least moment of inertia. Its axis of largest moment of inertia is perpendicular to the wing plane. According to the laws of mechanics, a freely spinning body which encounters a mechanism of energy loss will finally assume a rotation around its axis of largest moment of inertia. Pegasus satellites do lose energy because of eddy current losses and subsequent heat dissipation in the earth magnetic field, and possibly also because of flexing of the wings. In the course of time, their spin axes will change from the longitudinal direction to the direction of the axis of largest moment of inertia. Pegasus I underwent this change within a few days after launch (Figure 10). In Pegasus II and III, the transition to a flat spin is much slower. The reason for this slow transition is not yet known.

Meteoroid Sensors

When Project Pegasus was initiated, a careful study of existing meteoroid sensors was made which resulted in the selection of a sensor developed at the NASA-Langley Research Center. This sensor is basically a charged capacitor with a thin dielectric, a metal foil on one side, and a sheet of aluminum on the other side. When a meteoroid perforates the aluminum sheet and the other two layers, a momentary short between the metal plates is produced by the plasma cloud generated in the high velocity impact. The discharge current burns off any conducting bridges between the two metal layers and thus "heals" the capacitor after each perforation. The discharge pulse serves as a puncture indication. In its final form, after some further development, the sensor consisted of a trilaminate mylar dielectric, with a vapor-deposited copper layer on one side, and an aluminum sheet of 0.04, 0.2, or 0.4 mm thickness on the other side (Figure 11). A capacitor of this kind was attached to either side of a 2.5 cm thick layer of styrofoam. A Pegasus satellite carries 208 double-sided sensor panels of this design, each of the 416 sensors with an area of about 50 x 100 cm. Table I shows the total sensor areas for each of the three aluminum thicknesses. The voltage across the capacitor is 40 volts. A discharge pulse consists of a fast voltage drop from the 40-volt level, and a relatively slow rise during the recharging of the capacitor. Both the fast drop and the slow rise of voltage are used for hit indication, panel identification, and pulse verification. By careful adjustment and calibration of the electronic circuits, it was possible to discriminate between true perforation pulses and pulses caused by permanent shorts, interference, radiation-induced charges, and other false signals which might occur during flight. A diagram of the sensor electronic system is shown in Figure 12. A schematic of a digital "hit word" is illustrated in Figure 13; the numbers designate number of Bits.

Sensor Testing

Testing and calibrating of the meteoroid sensors was difficult because none of the existing high-speed particle ranges permitted the simulation of meteoroid velocities and particle masses as encountered in Pegasus flights. It is true that some facilities provide velocities up to about 30 km sec^{-1} ; however, these ranges are not yet sufficiently free from interferences and secondary particles to permit a true simulation of meteoroids in space. Testing and calibrating of the sensors, therefore, had to be done with particles of 5 to 10 km sec^{-1} velocity. These tests indicated that the sensors responded with clean pulses to at least 75%, and probably more, of the perforating hits. Figure 14 shows the percentage of recorded discharges as a function of the threshold voltage in the electronic discriminator circuit. They also revealed, however, that in a few percent of the simulated meteoroid hits, the sensors were left with permanent shorts. In view of the very large uncertainty factors of two or three orders of magnitude with which meteoroid abundance data were afflicted at the time when Project Pegasus was initiated, a possible error of 25% appeared tolerable. In total, several hundred clean test shots were obtained which met with a set of stringent test conditions. On the basis of these tests, the sensor panels were accepted for Pegasus flights.

The 0.2-mm and 0.4-mm sensors on Pegasus I suffered more losses from electric shorts, and from erratic operation, than had been expected. The reasons for these effects are not known at this time. It is believed that several causes worked together, among them the continuous changes of temperature during the day and night cycles; some spurious impurities which may have been left in or on the mylar dielectric; the attracting force between the two metal layers of the capacitors; and, possibly, effects of rugged edges of meteoroid punctures. As soon as a sensor is observed to be shorted or erratic, it is switched off by ground command. Unfortunately, the large number of Pegasus sensors (416) did not permit an individual command switch-off capability for each sensor. Only sensor groups consisting of two, six, or eight panels can be switched off by one command.

The continuous process of quality improvement during sensor manufacturing, together with some changes in test procedures and sensor wiring, resulted in better sensor lifetimes on Pegasus II and III. After manufacturing, each sensor was subjected to a short voltage pulse of 200 volts which "burned out" all near-shorts. Also, each sensor was equipped with a fuse which can be blown by ground command after the internal resistance of this particular sensor has dropped below a certain value. By these precautions, the number of intact sensors could be kept much higher on Pegasus II and III than on Pegasus I. Table III shows the numbers of operating sensors on the three Pegasus satellites on the indicated dates.

Meteoroid Puncture Data

The three Pegasus satellites were launched from Cape Kennedy on February 16, May 25, and July 30, 1965. Ground operations are concentrated in the Satcon Station at Cape Kennedy; data from the satellites are received by several stations around the world (Figure 15). The stored data which are transmitted from the memory upon ground command are received by stations under the control of the Goddard Space Flight Center. All data are reduced and analyzed at the Marshall Space Flight Center. Meteoroid numbers have been recorded as listed in Table IV. The table also shows puncture rates per m^2 and day, and rates per m^2 and year.

The puncture rates measured by Pegasus II and Pegasus III agree remarkably well. Pegasus I provided a somewhat lower rate in the 0.04-mm sensors. Possibly, this difference is caused in part by the different spinning mode in connection with a directionality of the meteoroids. In Figure 16, some of the puncture data are plotted as a function of time. This figure also shows the periods during which meteoroid showers occurred. Although it appears as if a correlation between counting rate and shower activity existed, a more elaborate analysis of satellite attitude must be accomplished before a true increase in counting rate can be established.

The puncture rates measured by the Pegasus satellites are shown in Figure 17, together with results from Explorers 16 and 23, and with theoretical results obtained by F. Whipple in 1963 [1] . In this figure, the Pegasus data points are average numbers between Pegasus I, II, and III. The abscissa in this diagram shows panel thickness in mm, regardless of panel material. Explorers 16 and 23 carried pressure cans out of steel and copper-beryllium. Their puncture rates agree well with those measured by Pegasus, referred to the same thickness in mm, irrespective of the target material. This result is somewhat surprising; on the basis of existing theories, the puncture rates in steel and beryllium-copper would have been expected to be lower by about a factor of ten than the puncture rate in aluminum of the same thickness. Possibly, the difference in the design of the sensors may account for part of this apparent discrepancy. Ground tests are presently in preparation to study the relative response of the two sensor types.

It is obvious that the puncture rate for 0.04-mm target sheets is considerably lower than the theoretical estimate. The measured rate for 0.2-mm Al is close to the "best estimate" line, and the 0.4-mm Al rate falls between the "best estimate" and the "pessimistic" lines. The error margins of the data points are very difficult to estimate at the present time. They have to include the statistical error, the possibility of imperfect response of the sensors as indicated in ground tests, errors possibly caused in the data system, and errors from other sources. It is believed that the data points have an uncertainty of not more than about ±30%.

The correlation between meteoroid mass and puncture capability is still poorly known. On the basis of theoretical data presented in Reference 1, it may be assumed that meteoroids of about 10^{-4} g and 30 km $\sec^{-1}$ velocity are capable of penetrating 2 mm of aluminum. From this mass on upward, Whipple [1] reported abundance data derived from optical and radar measurements which fall on the "best estimate" line. The 0.4-mm data point measured by Pegasus seems to favor the "pessimistic" line more than the "best estimate" line. Quite obviously, the three Pegasus data points do not permit a reliable extrapolation to larger thicknesses and higher meteoroid masses.

Measurements with thicker target sheets would be very desirable. Unfortunately, expected perforation rates through thicker panels are quite low. Based on the data obtained by Pegasus satellites in conjunction with Whipple's theoretical estimates, a Pegasus-size sensor with a 1-mm Al sheet may be expected to be perforated about 10 to 40 times per year; a sensor with a 2-mm Al sheet only 1 to 3 times per year. Larger sensor areas, or multiple flights, would be desirable for these experiments.

REFERENCE

1. F. L. Whipple, "On Meteoroids and Penetration," Smithsonian Astrophysical and Harvard College Observatories, Cambridge 38, Mass., 1963.

TABLE I

METEOROID SENSOR AREAS

TOTAL AREA	THICKNESS	MATERIAL
8 m^2	0.04 mm	Al 1100
16 m^2	0.2 mm	Al 2024
176 m^2	0.4 mm	Al 2024

TABLE II

RANGES OF PEGASUS TEMPERATURES
(Deg. K)

Component	Design Range	Actual Range
Radiation Detector	222° - 388°	230° - 320°
Batteries	272° - 322°	290° - 314°
Electronic Components	262° - 332°	275° - 330°
Solar Panels	222° - 388°	210° - 340°
Meteoroid Sensors	167° - 394°	225° - 385°

TABLE III

NUMBERS OF OPERATING SENSORS ON PEGASUS SATELLITES

Al Thickness	0.04 mm	0.2 mm	0.4 mm
Initially	16	34	366
Pegasus I (Sept. 5, 1965)	14	-	-
Pegasus II (Sept. 2, 1965)	16	32	289
Pegasus III (Oct. 8, 1965)	16	10	306

TABLE IV

PEGASUS METEOROID DATA
(On the Dates Indicated)

Thickness	0.04 mm			0.2 mm			0.4 mm		
Pegasus	I	II	III	I	II	III	I	II	III
Date	9/5	9/2	10/8	†	9/2	10/8	†	9/2	10/8
Total No. of Hits	125	121	71	-	18	14	-	58	41
Punctures per m^2 Day	0.12	0.19	0.16	-	0.015	0.014	-	0.004	0.004
Punctures per m^2 Year	44	70	58	-	5.5	5.1	-	1.45	1.45

†Operating times of these sensors were too short to yield meaningful data.

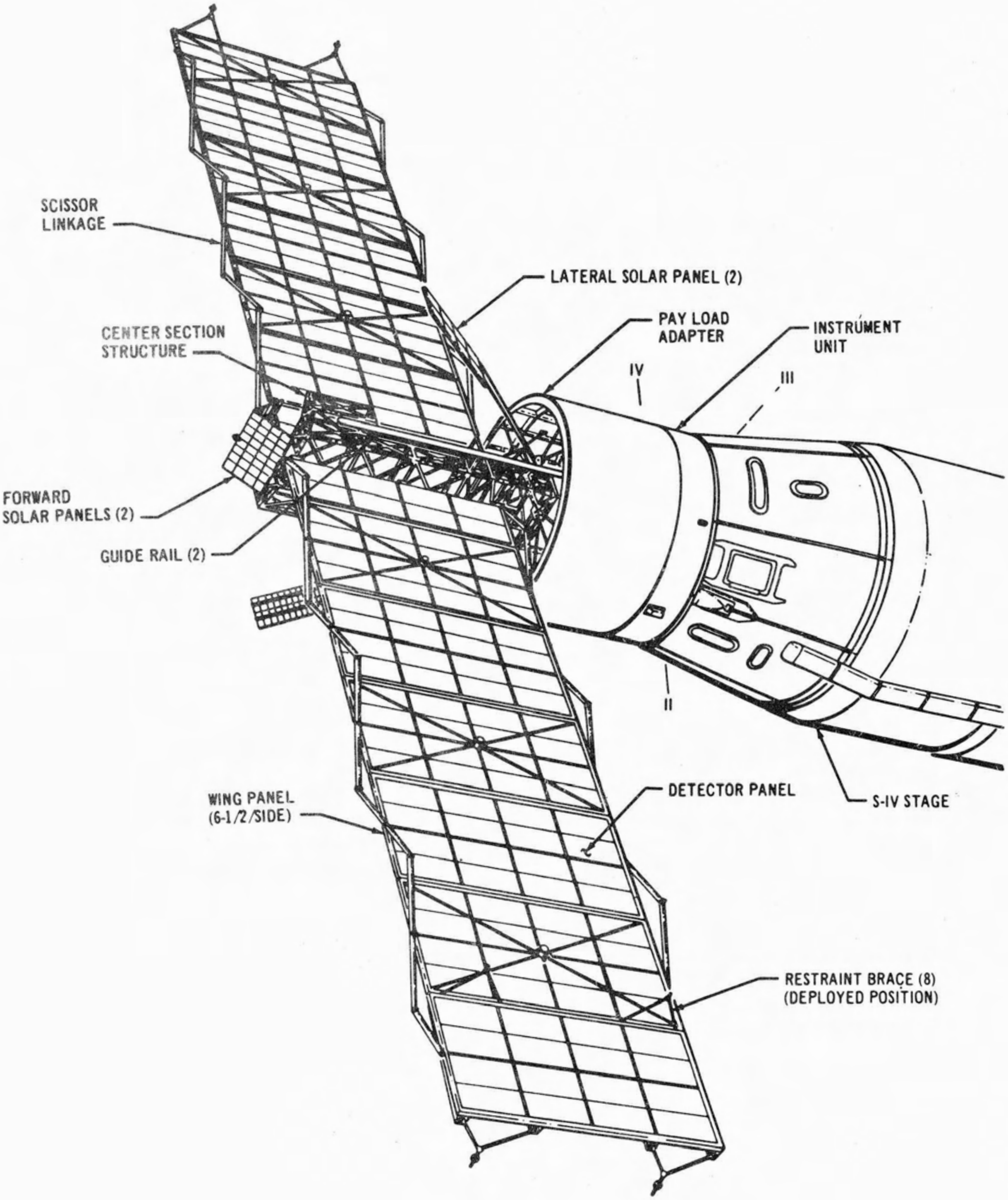

FIG. 1 - METEOROID-MEASURING SATELLITE

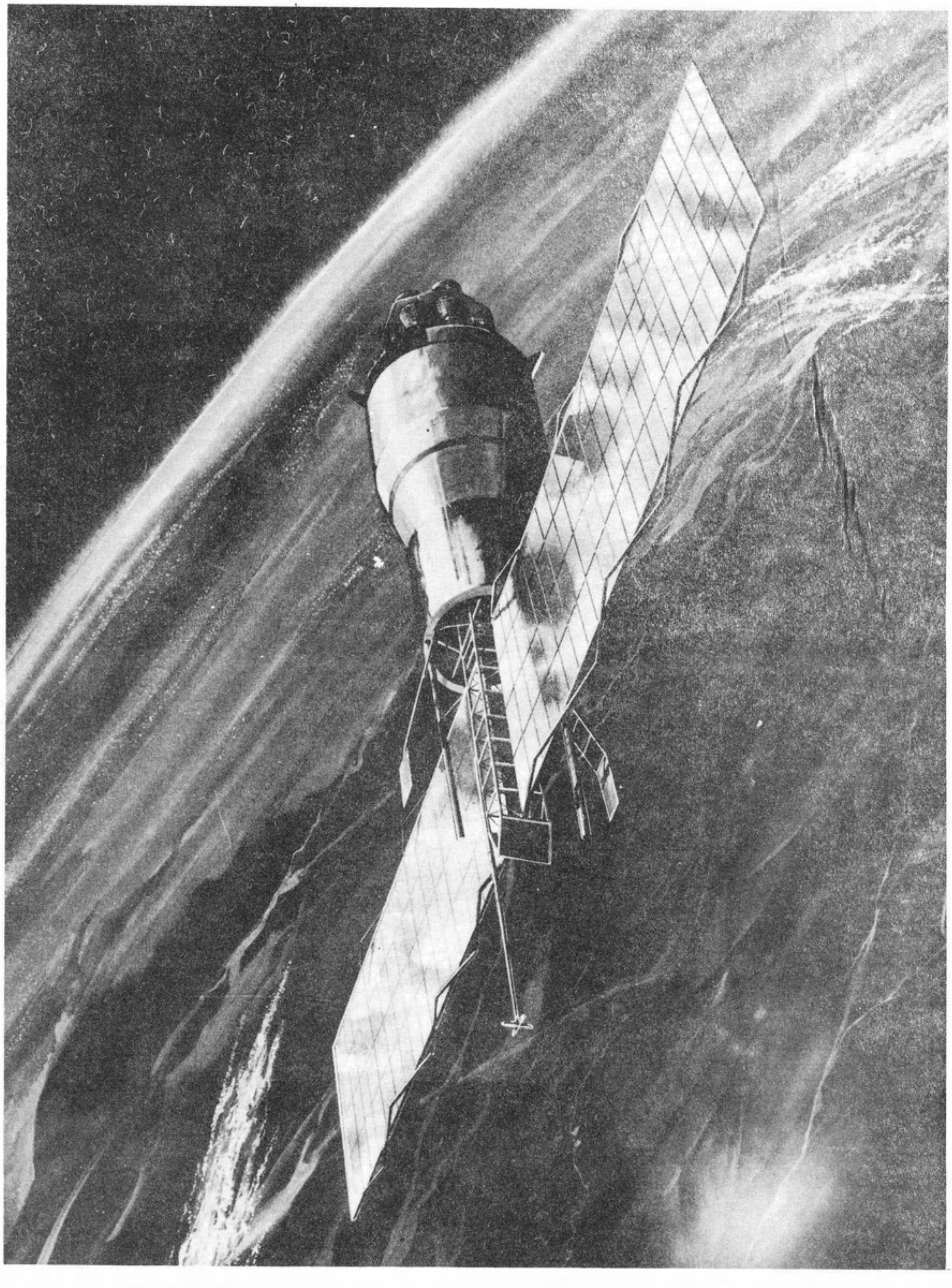

FIG. 2 - ARTIST'S PICTURE OF PEGASUS SATELLITE IN ORBIT

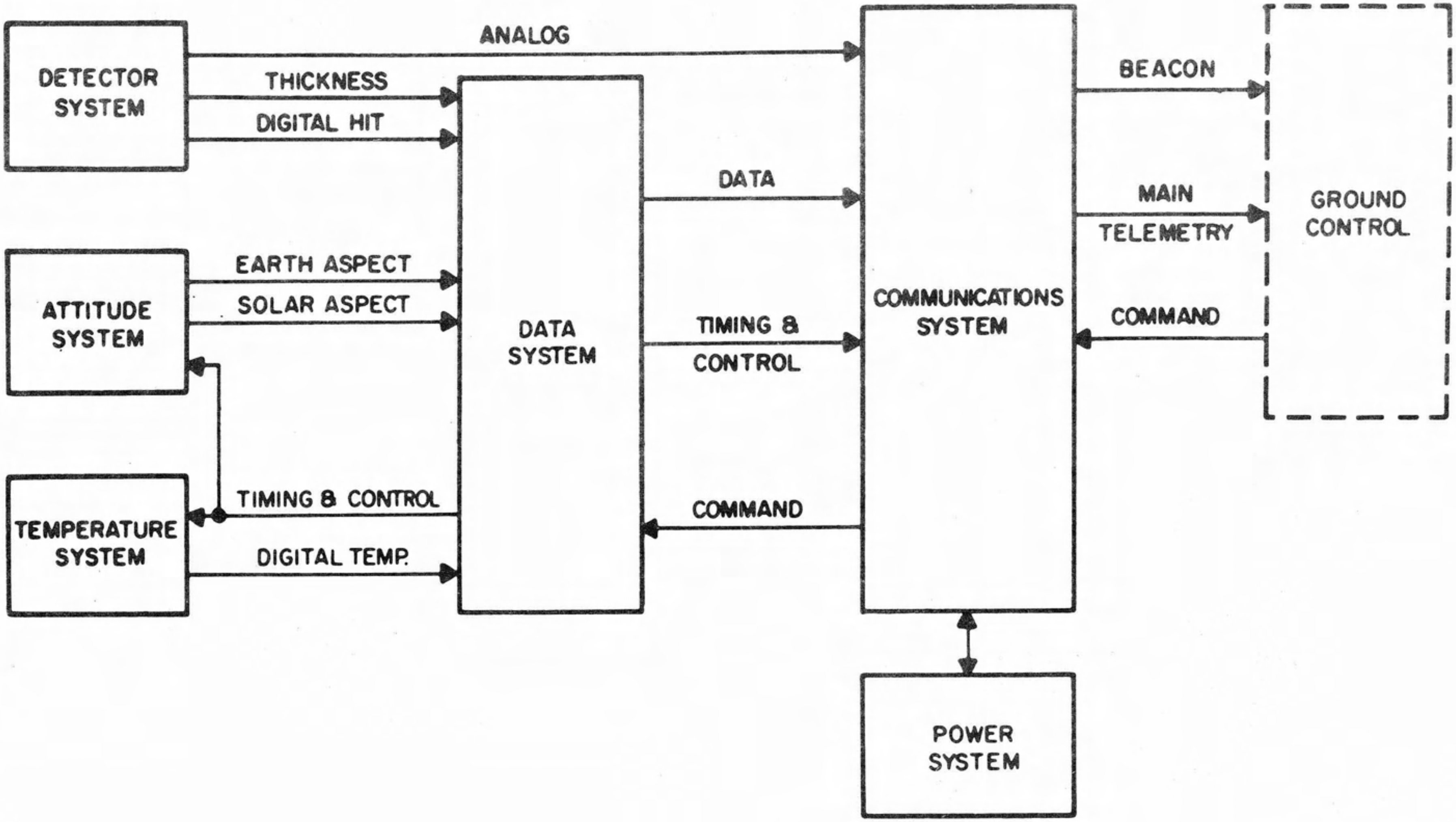

FIG. 3 - ELECTRONIC SYSTEM

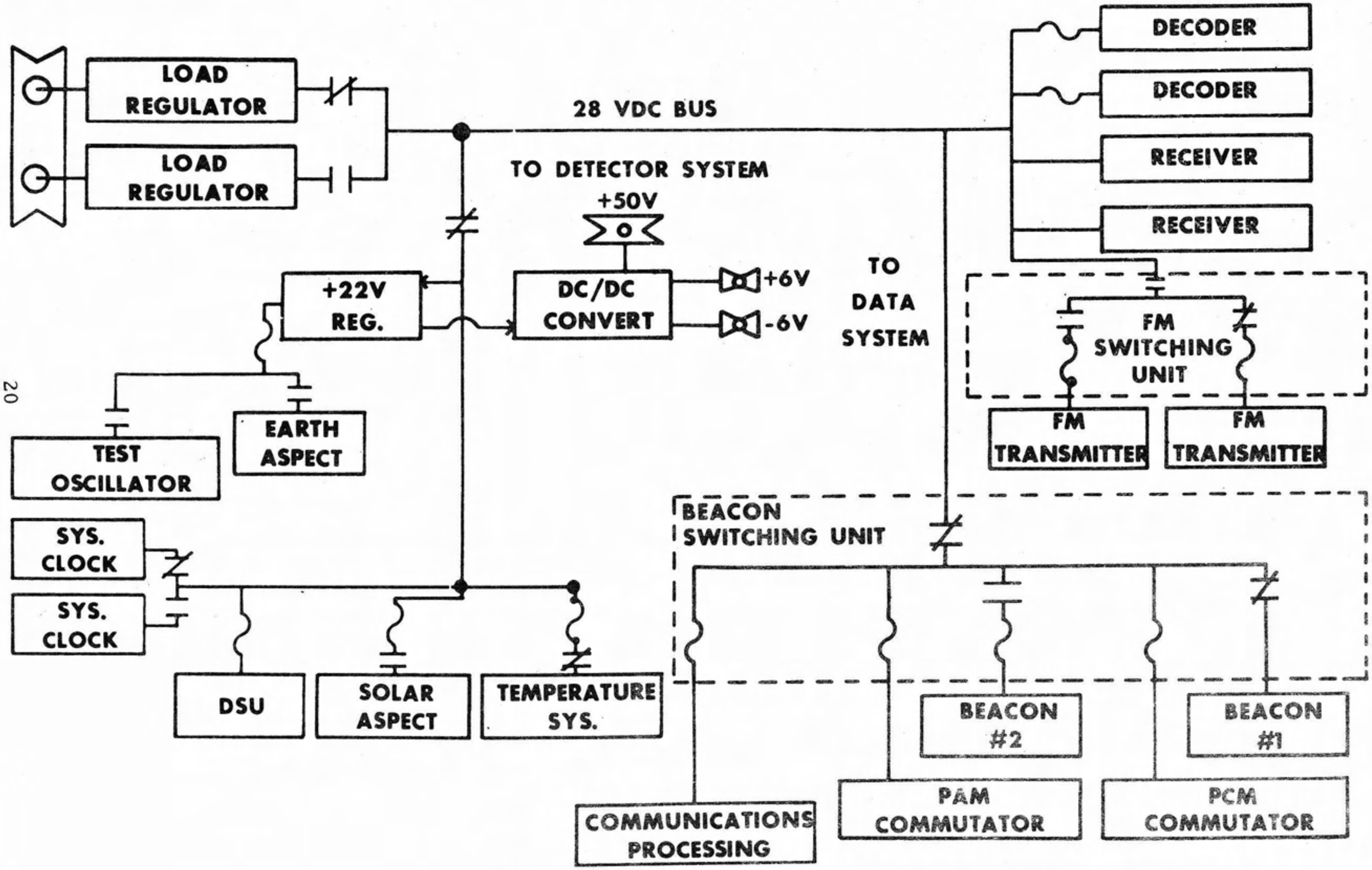

FIG. 4 - POWER DISTRIBUTION

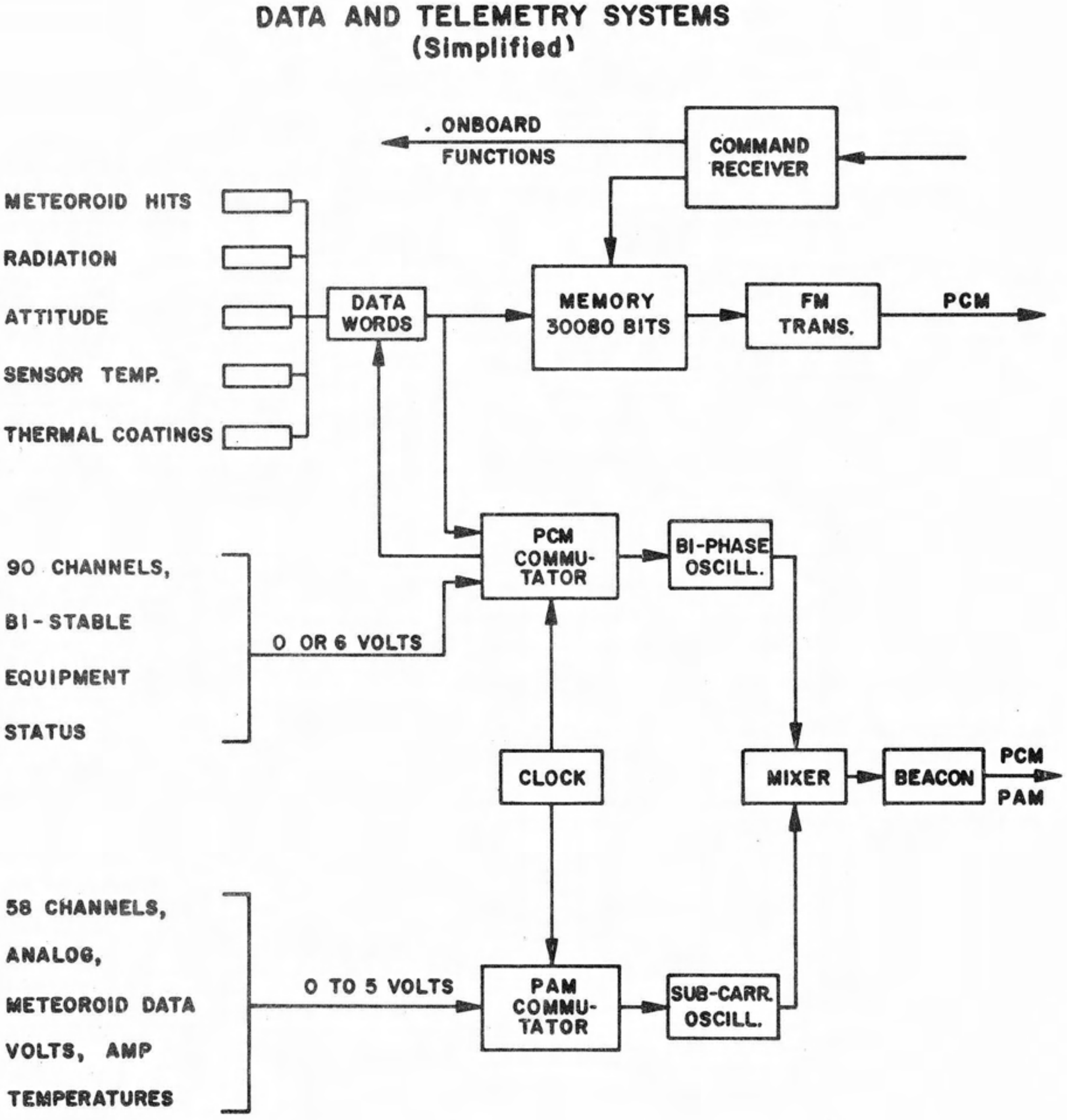

FIG. 5 - DATA AND TELEMETRY SYSTEMS (SIMPLIFIED)

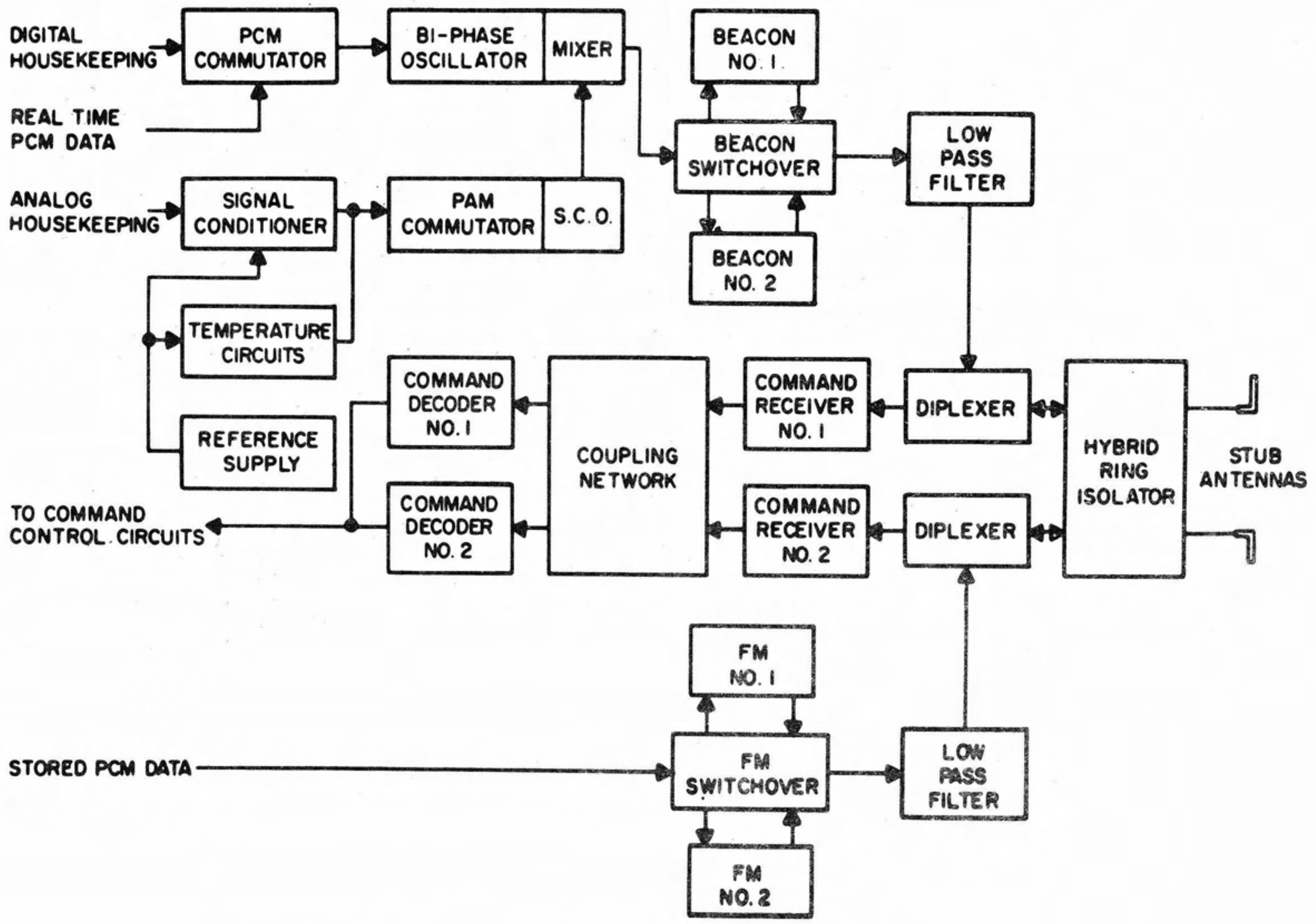

FIG. 6 - COMMUNICATIONS SUBSYSTEM

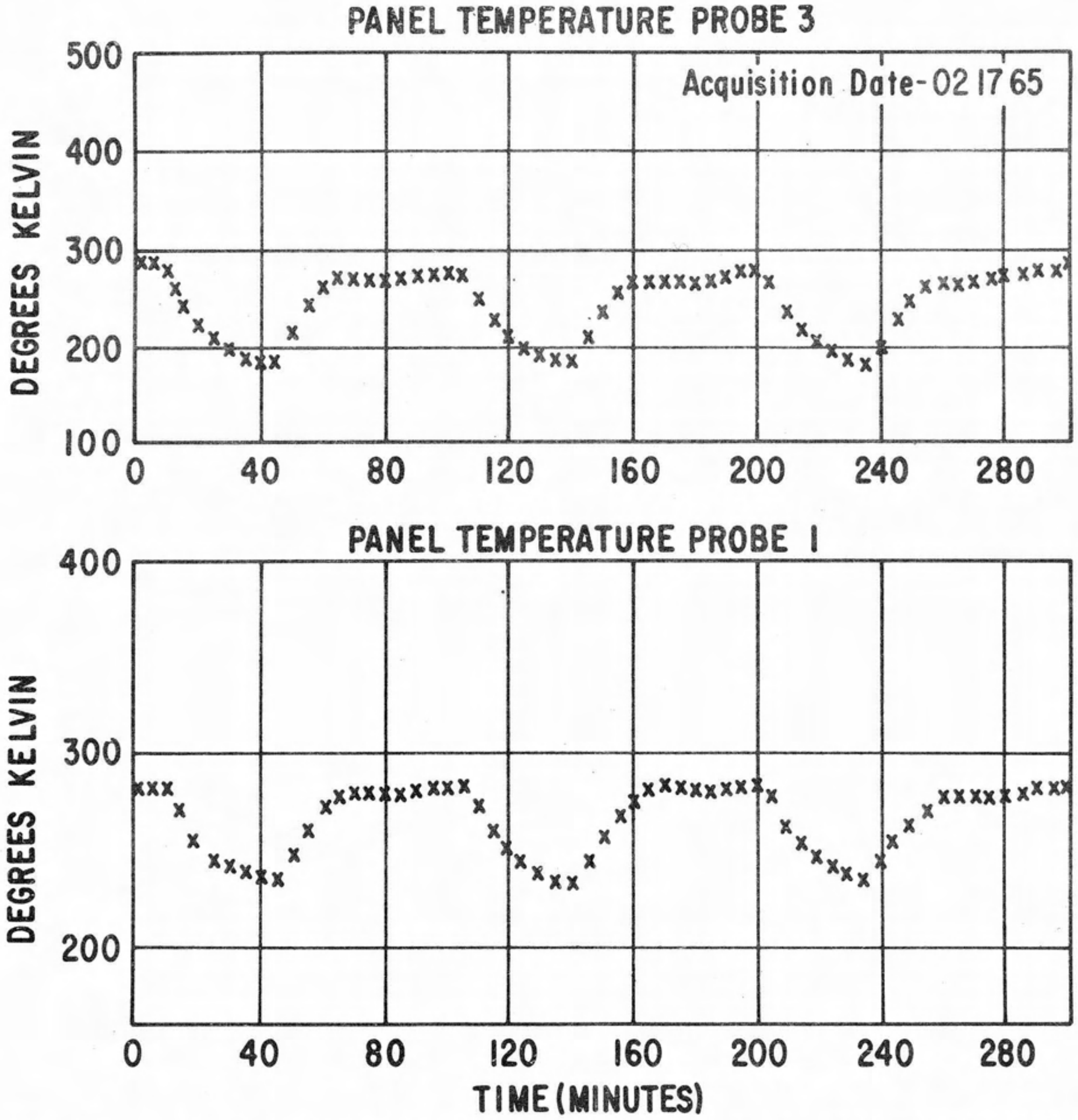

FIG. 7 - SAMPLES OF TEMPERATURE MEASUREMENT ON METEOROID SENSORS

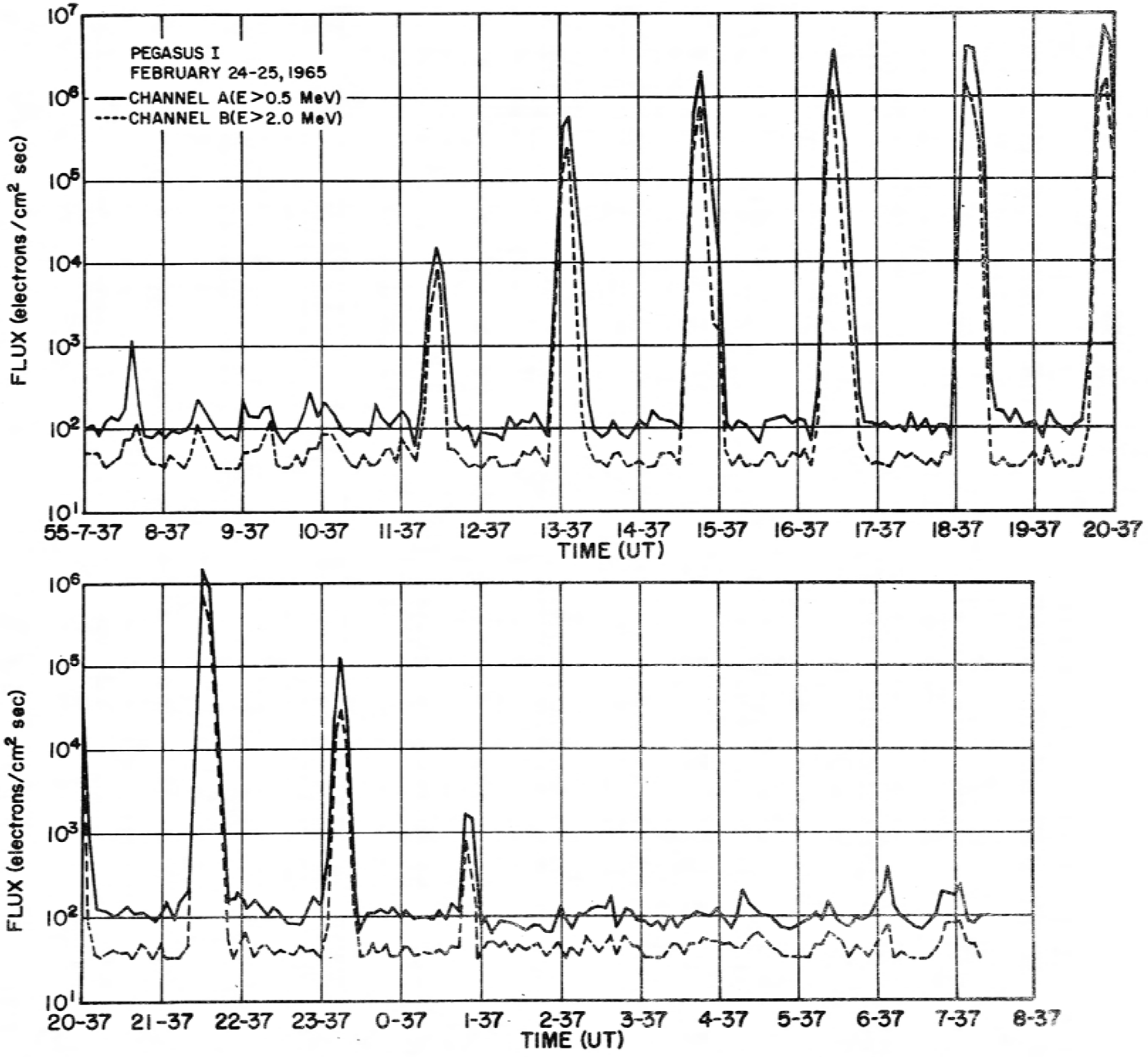

FIG. 8 - RADIATIÓN FLUX HISTORY FOR 24 HOUR PERIOD, PEGASUS I

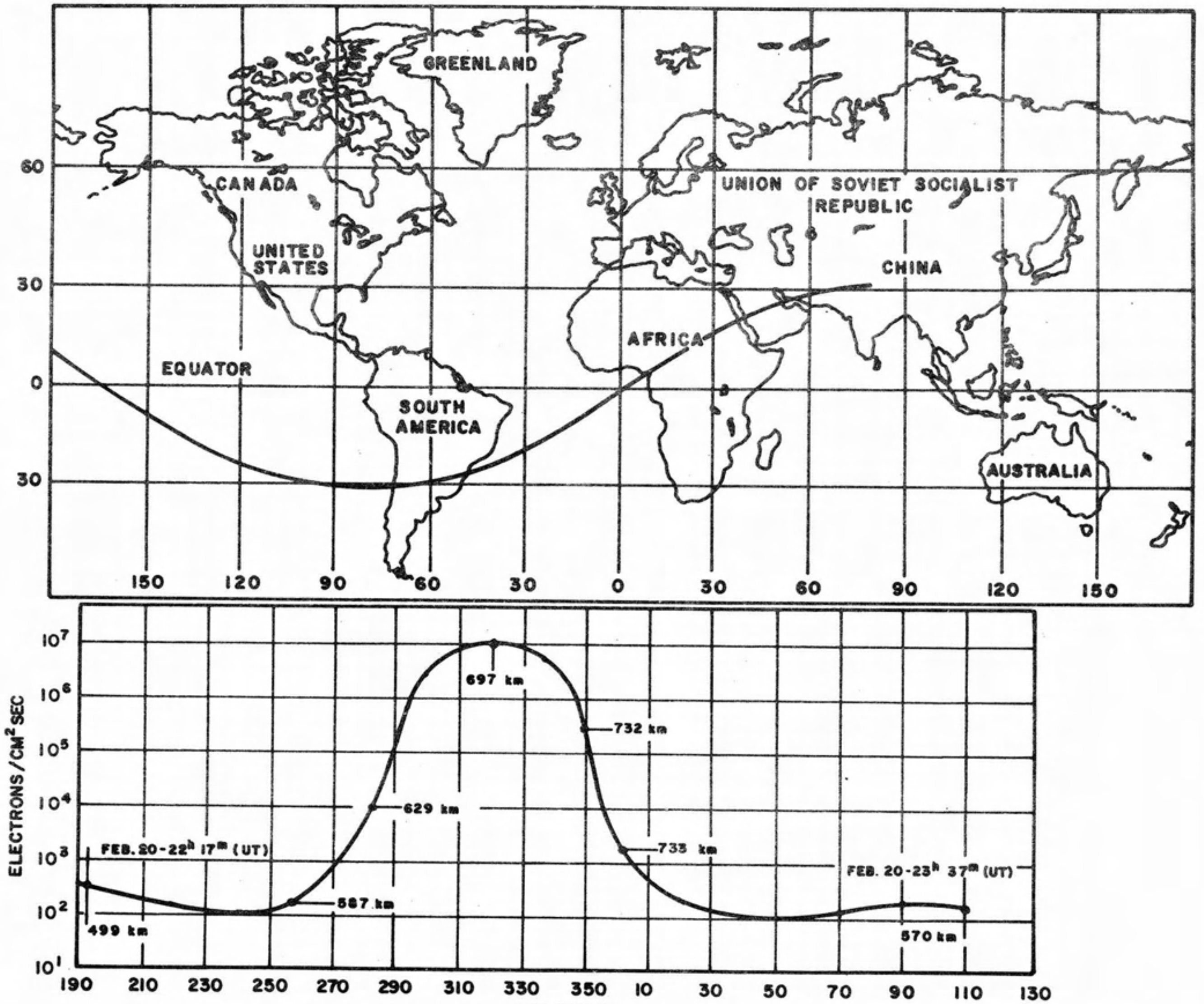

FIG. 9 - ORBIT AND FLUX HISTORY FOR SINGLE PASS THROUGH SOUTH-ATLANTIC ANOMALY, PEGASUS I

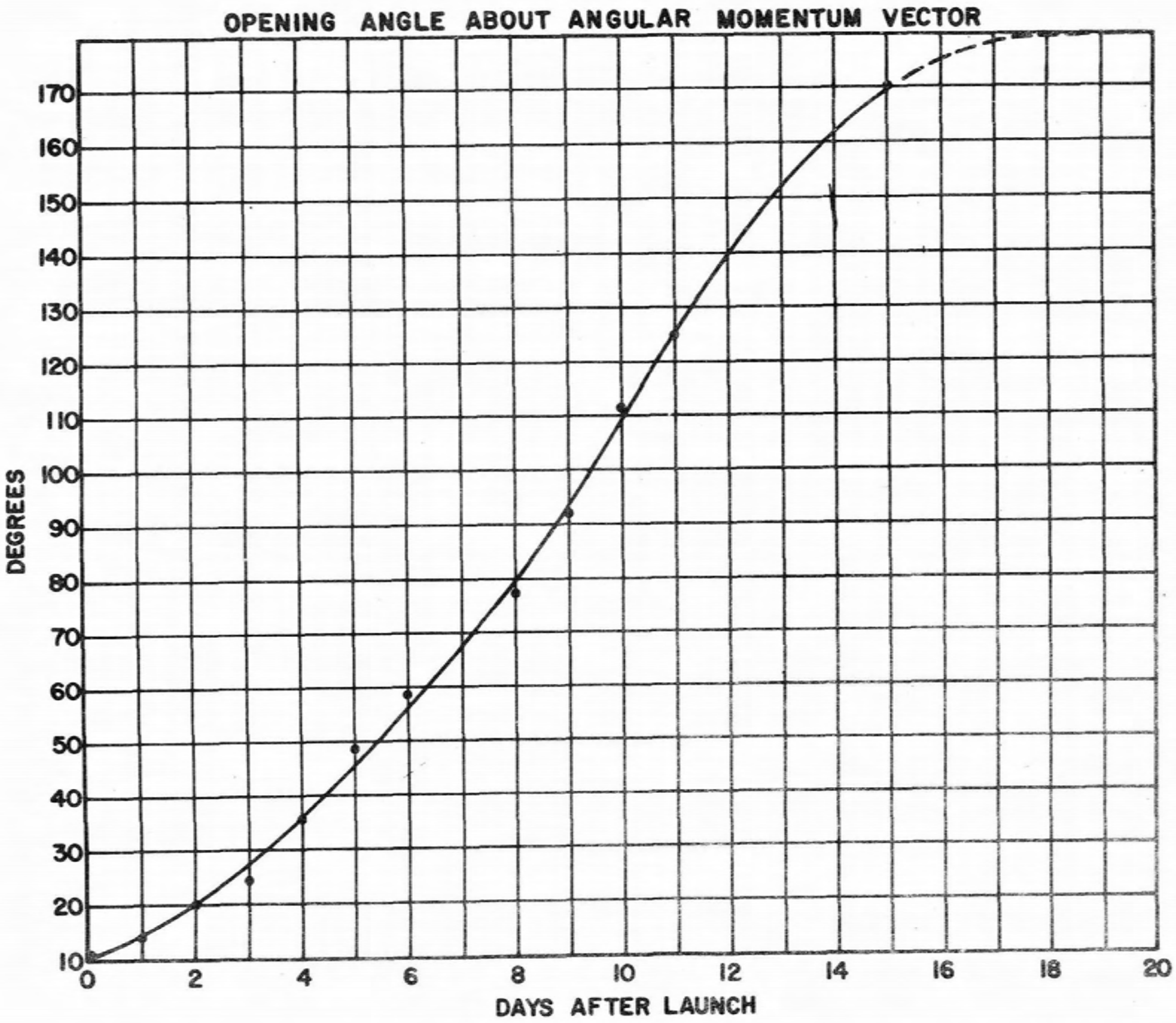

FIG. 10 - OPENING ANGLE ABOUT ANGULAR MOMENTUM VECTOR OF PEGASUS I

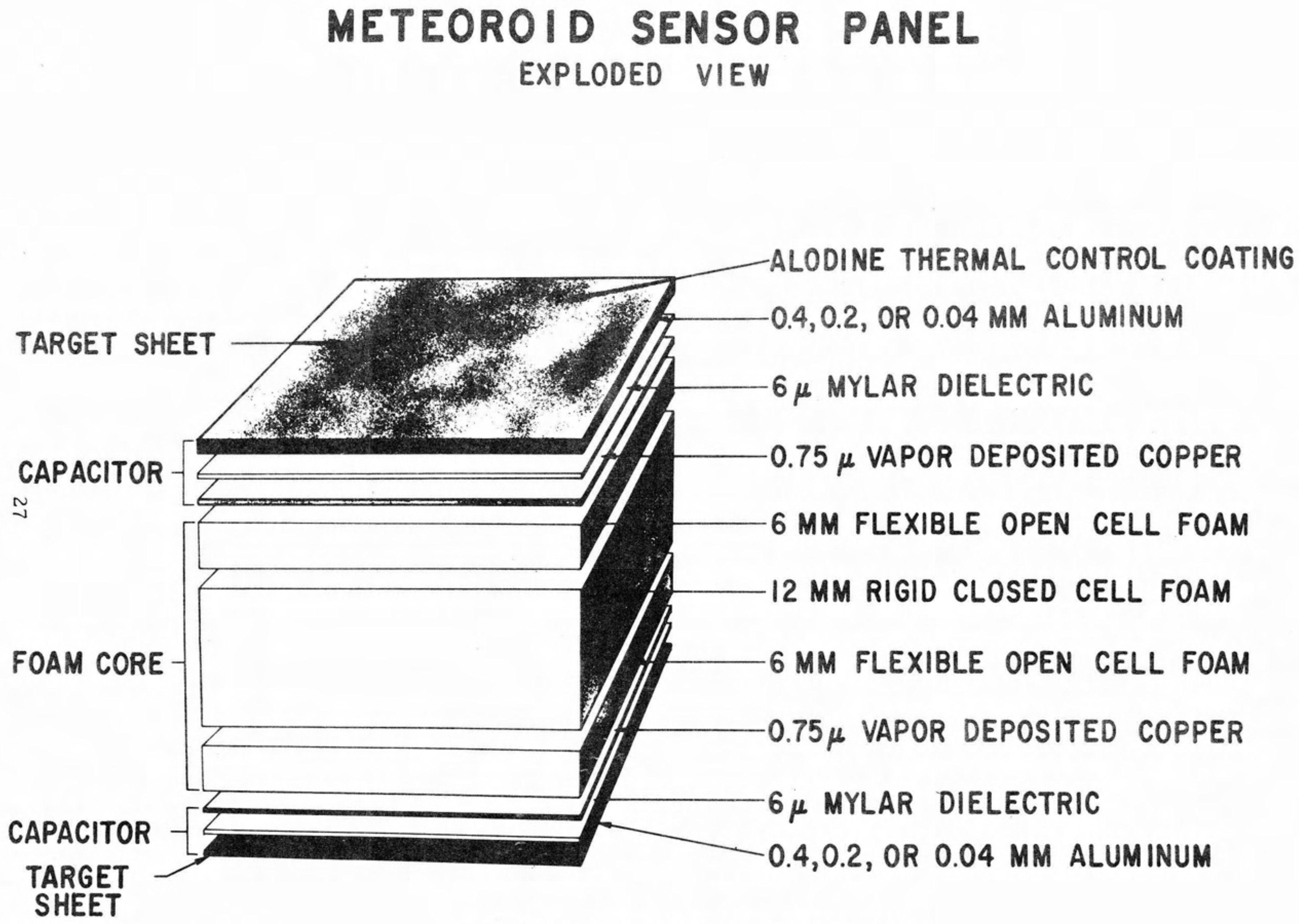

FIG. 11 - METEOROID SENSOR PANEL

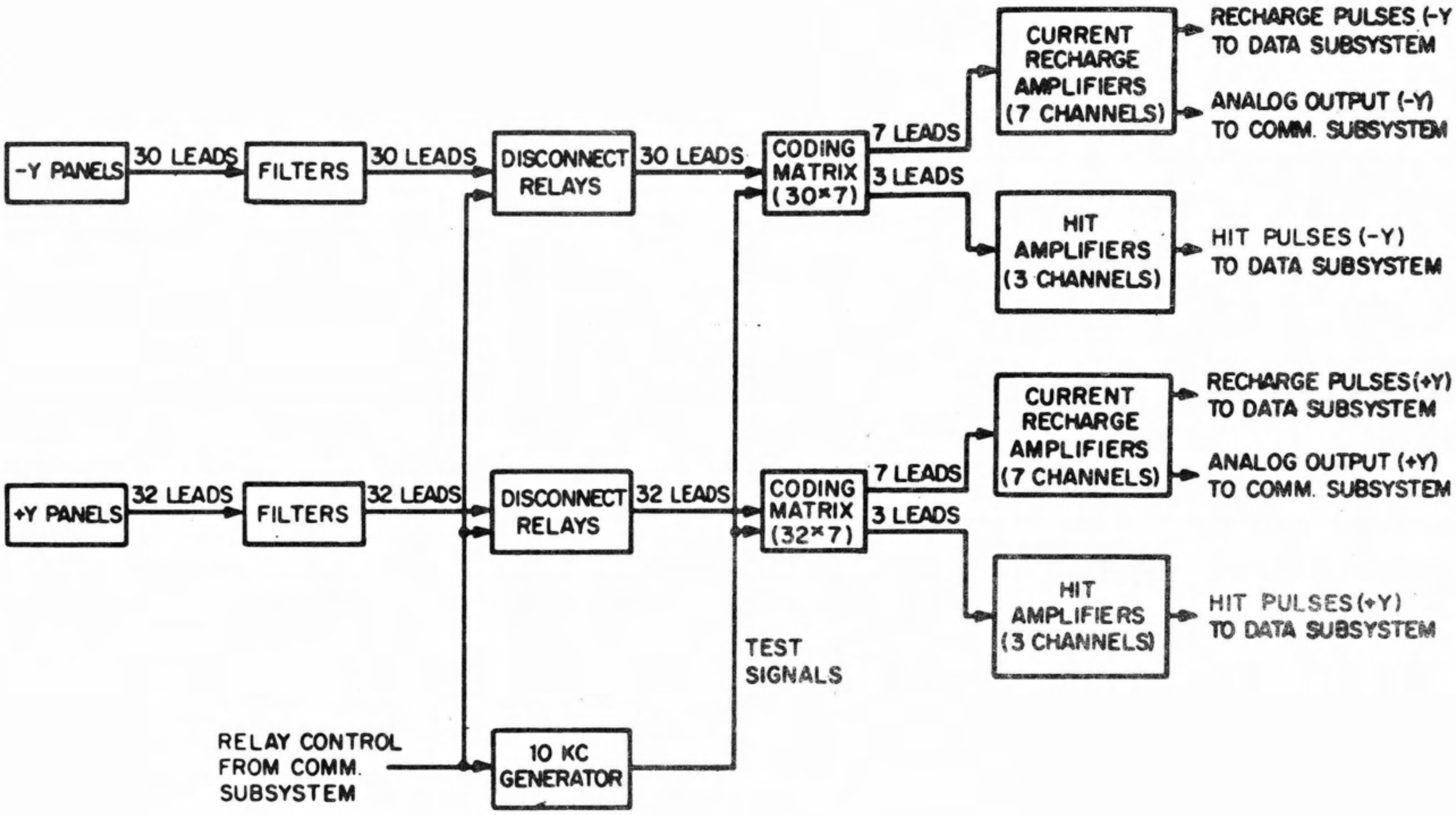

FIG. 12 - METEOROID SENSOR SUBSYSTEM

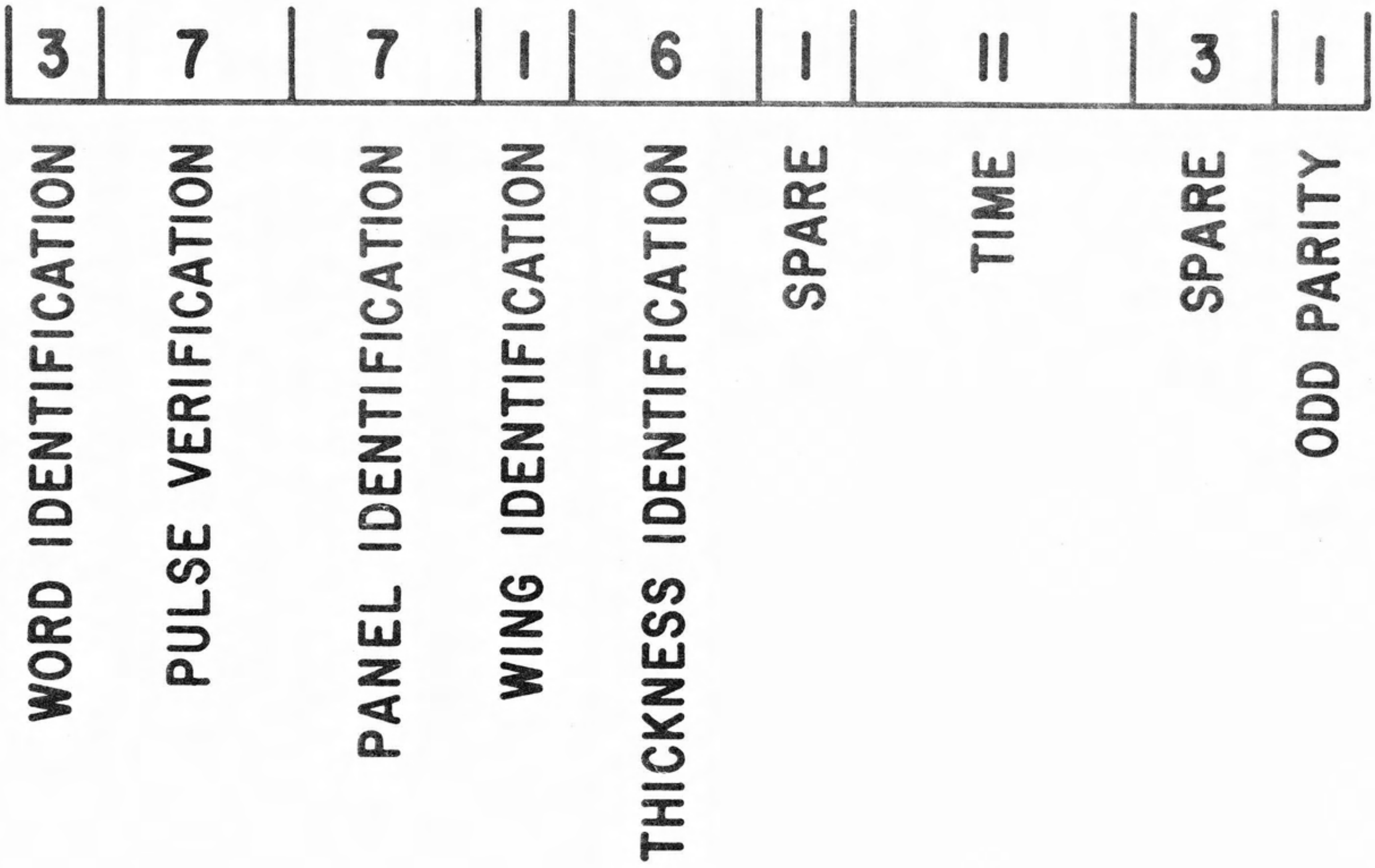

FIG. 13 - METEOROID HIT WORD FORMAT

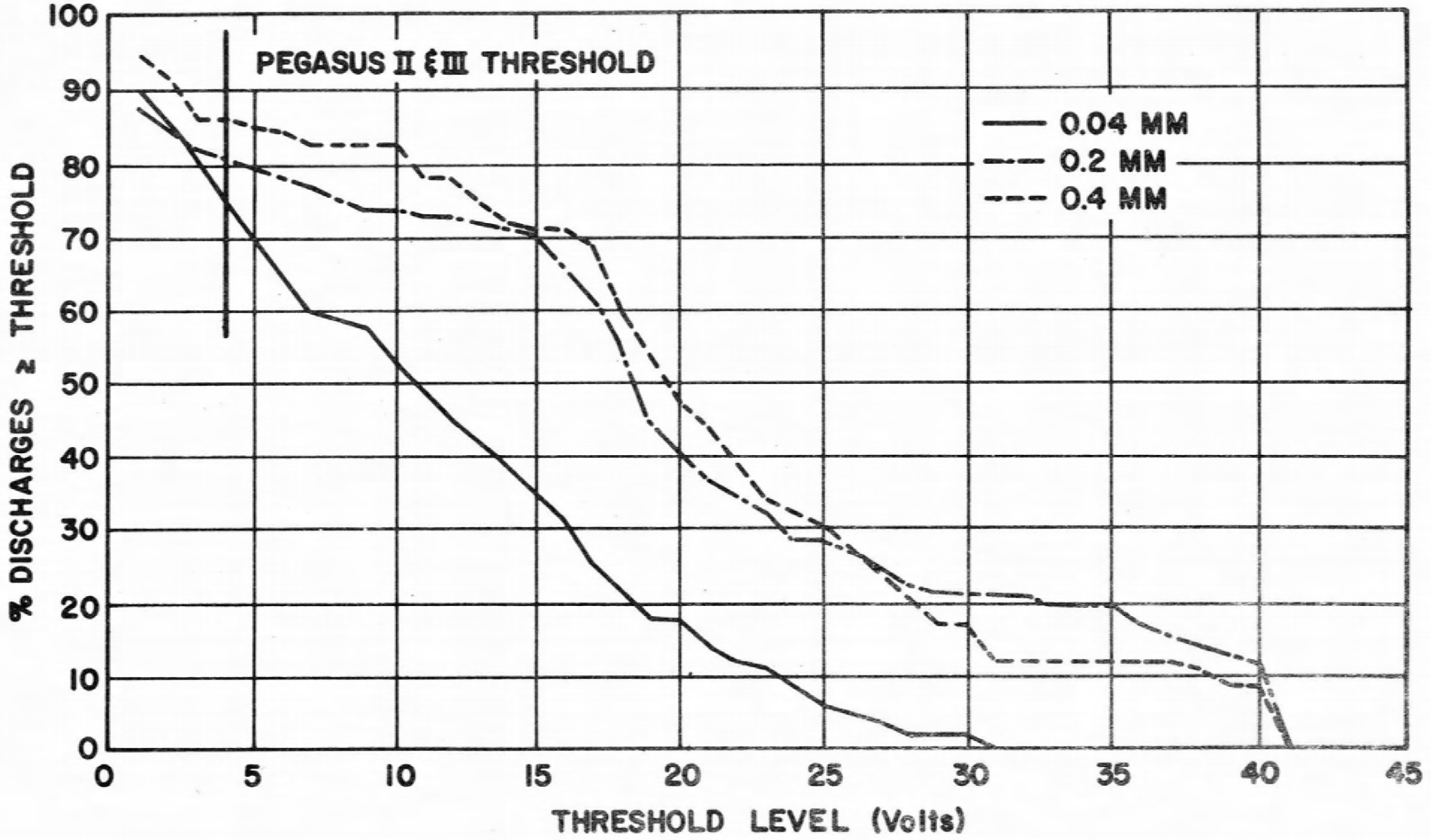

FIG. 14 - RESPONSE OF PEGASUS SENSORS TO SIMULATED METEOROID PUNCTURES

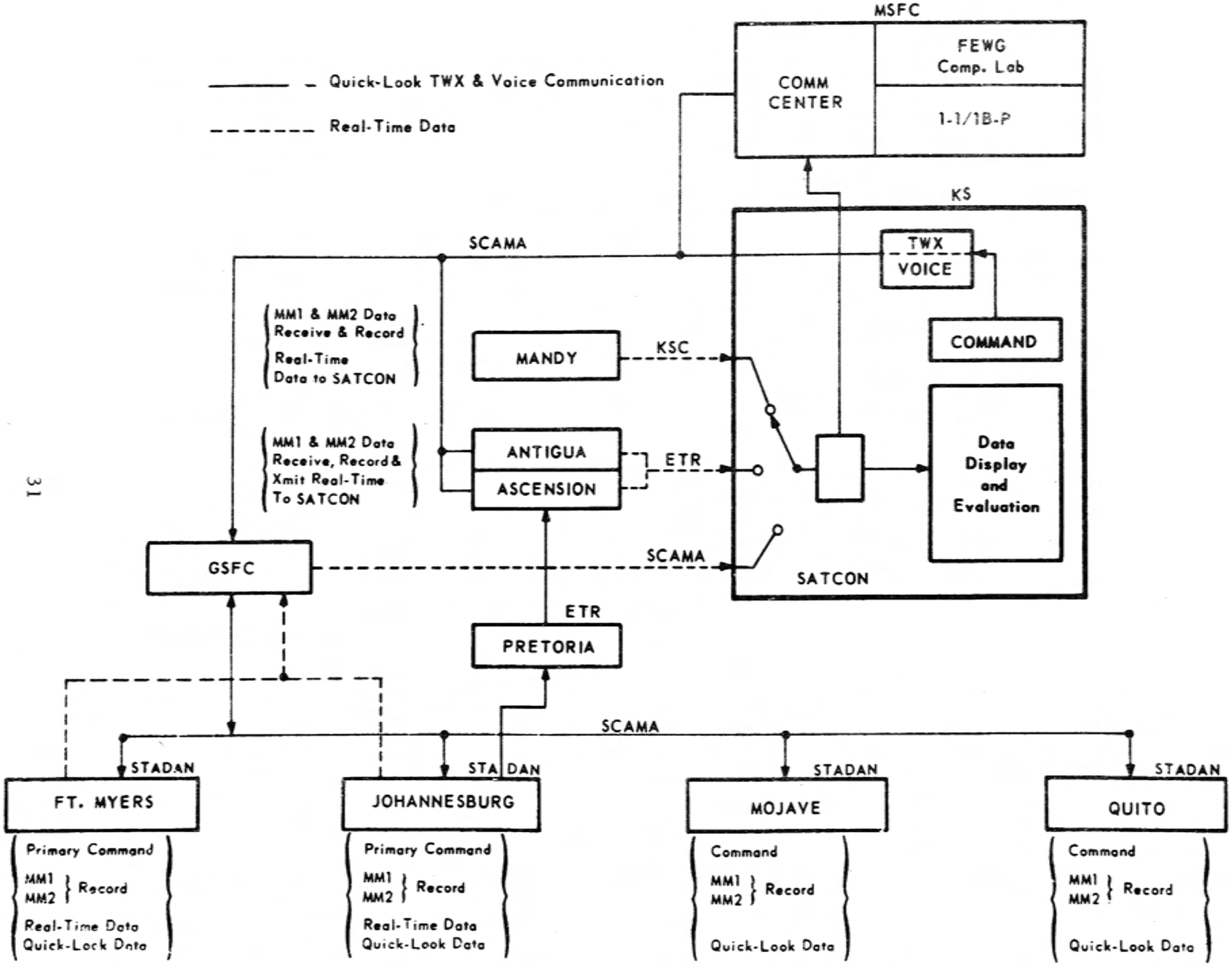

FIG. 15 - PEGASUS DATA ACQUISITION AND OPERATIONAL COMMAND NETWORK

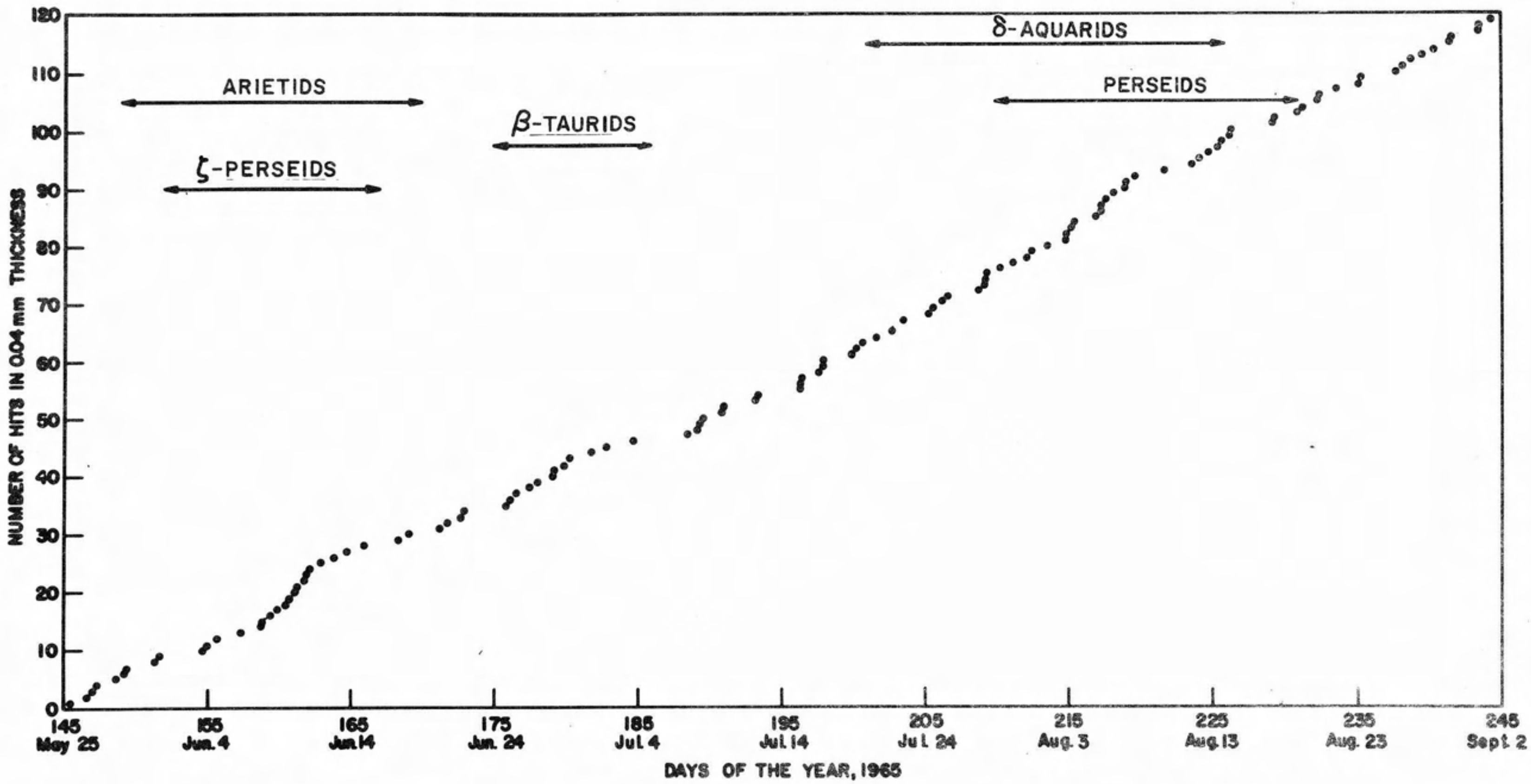

FIG. 16 - TIME HISTORY OF ACCUMULATED PENETRATIONS FOR 0.04 MM PANELS ON PEGASUS II

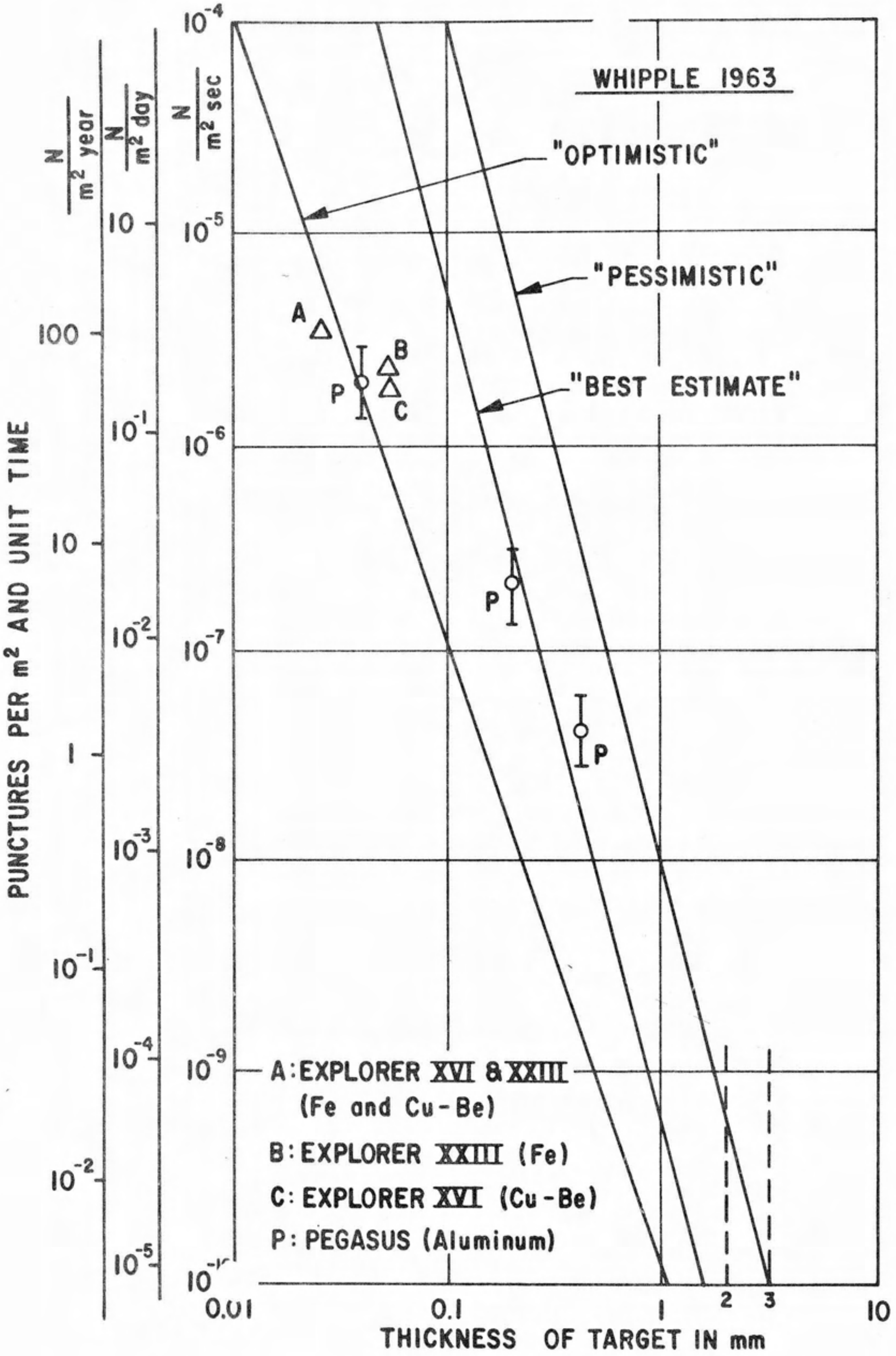

FIG. 17 - EXPERIMENTAL AND THEORETICAL METEOROID PUNCTURE DATA