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MEASUREMENTS ON THE SATURN SPACE VEHICLE*

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ABSTRACT

The history of man might be considered as an ever increasing quantity and quality of measurements. Measurements related to space have been made by early astronomers, modern astronomers, and now by aerospace technologists. The manned lunar landing, a major national goal, has given us the means to measure in space. The space vehicle development itself has made heavy demands on instrumentation; this is discussed in some detail in this paper. The advantages of the International System of Units are mentioned. Some examples are used to illustrate the future of space measurement.

ASTRONOMY

All of us in this room share a common interest: that of making measurements. From our viewpoint we might consider the history of man to be an ever increasing quantity and quality of measuring technology. From earliest times man has turned his attention to the heavens and pondered how he might know more about the mysteries there — in other words, how he might measure the heavenly phenomena. Even before the invention of the telescope, rather precise measurements were made by men like Copernicus and Tycho Brahe. With Galileo's and Kepler's discoveries came a new era of astronomy, and a new era of space measurement. This era extends to the present day.

Large scale research with large rockets began shortly after the second world war. Progress has been rapid, with a major step being taken about ten years ago when orbital spacecraft entered the scene. These vehicles have given us new means to measure the mysteries of the heavens. Their development required the evolution of a new technology which itself has required application of measurement science.

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Figure One shows two early Egyptians using the merkhet. This was a simple sighting rod with a slit sight. Two plumb-lines were suspended in the plane of the observer's meridian, that is, along a north-south line. Sightings of star transits could be accurately made. This could be used to establish the north-south line, to determine the length of the year, and to mark the seasons(1).

In the second centruy B.C., Hipparchus used a thin metal ring with its plane fixed parallel to the earth's axis to determine the time of equinoxes. At the equinoxes the sun lies in the plane of the earth's equator, and the shadow cast by the front of the ring falls exactly on the back. With this, Hipparchus discovered the precession of the equinoxes(1).

A similar, but much more sophisticated instrument was Tycho Brahe's great equatorial armillary, shown in Figure Two. With it, and other non-optical instruments, in the latter part of the sixteenth century, Tycho collected very accurate data on the motions of the planets. These data were the basis for Johann Kepler's formulation of the laws of planetary motion in the early seventeenth century. Through Kepler's laws, Isaac Newton was able to arrive at his great system of universal dynamics(1).

"Less than a century separated the work of Newton from that of Kepler, but in that time the intellectual climate had changed enormously. The man primarily responsible was Galileo Galilei." (Quoted from Reference 1.) Galileo, whose portrait is Figure Three, gave us not only new instruments and new discoveries, but also the beginnings of experimental physics. He did not invent the telescope, but he quickly put it to work. At last, with optical instruments, men could make accurate measurements of the heavens.

THE SATURN PROGRAM

A milestone in man's attempt to measure phenomena related to the earth was the International Geophysical Year (IGY). From it came many measurements of our planet and near-by space — and from it came the discovery of the Van Allen radiation belts in 1958. We saw a major emphasis placed on space exploration culminating in establishment of the manned lunar landing as a major national goal. This was initiated in President Kennedy's second State of the Union message to the Congress on May 25, 1961:

> "With the advice of the Vice President, who is Chairman of the National Space Council, we have examined where we (the U.S.) are strong and where we are not, where we may succeed and where we may not...

Now is the time to take longer strides — time for a great new American enterprise — time for this Nation to take a clearly leading role in space achievement which in many ways may hold the key to our future on Earth...

Recognizing the head start obtained by the Soviets with their large rocket engines...we nevertheless are required to make new efforts on our own...This is not merely a race. Space is open to us now; and our eagerness to share its meaning is not governed by the effort of others. We go into space because whatever mankind must undertake, free men must fully share...

First, I believe that this Nation should commit itself to achieving the goal, before this decade is out, of landing a man on the moon and returning him safely to earth. No single space project in this period will be more impressive to mankind, or more important for the long-range exploration of space; and none will be so difficult or expensive to accomplish... It will not be one man going to the moon—if we make this judgment affirmatively, it will be an entire nation.."(2)

The manned lunar program is being accomplished by the Saturn launch vehicles and Apollo spacecraft. The Saturn family of vehicles is shown in Figure Four. The Saturn I vehicles are used for tests and operations in earth orbit, while the Saturn V is the actual carrier for the manned lunar operations. Development of the Saturn/Apollo has been carried out under direction of NASA's Office of Manned Space Flight (OMSF) by the Manned Spacecraft Center (MSC), the George C. Marshall Space Flight Center (MSFC), and the John F. Kennedy Space Center (KSC).

Development of the Saturn launch vehicles is being accomplished by Marshall Space Flight Center and its contractors. During the development, measurements, both on the ground and in flight, played a key role.

MEASUREMENTS ON THE SATURN

During the early development phases of launch vehicle design it is important to know how well flight conditions have been predicted, and how well the test vehicles are withstanding these conditions. To provide this information, each stage of each of the earliest Saturn vehicles has had an extensive instrumentation system. Later, as the vehicles have proven themselves, they are considered operational, and the quantity of instrumentation is reduced. The instrumentation is monitored during ground static firings of each stage, during factory checkout, during launch site checkout at Kennedy Space Center, and finally during flight by means of radio telemetry. Figures Five and Six show the number of flight measurements on the uprated Saturn I and Saturn V, respectively. A development flight of the Saturn V carried nearly 2800 measurements whose data are transmitted back to ground stations by 21 telemetry links.(3) The first two stages (S-IC and S-II) do not reach orbital velocity; they fall into the Atlantic Ocean. Data from them are recorded by a string of stations located along the flight path. The S-IVB stage, the Instrument Unit (IU), and the Apollo modules all go into orbit in the usual mission. Data from the orbiting S-IVB and IU are telemetered to ground stations of the Manned Space Flight Network (MSFN) as long as the on-board batteries last — usually about six hours.

Some critical measurements have their data displayed in real time at the Mission Control Center (MCC) in Houston, Texas. Decisions on modifications in the flight mission could be made based on these data. A majority of the measurements are recorded on magnetic tape at each ground station and are subjected to intensive study immediately after the flight. A "quick-look" report is issued very soon, interim reports on various systems follow, and a final evaluation report is issued 60 days after the launching.

The basic mission of Marshall Space Flight Center is the development of the launch vehicles. The large number of flight measurements made during the early "research and development" flights provide the confidence (or lack of it!) that the design is correct. The results of these measurements are used by the design engineers to confirm previous ground testing or to indicate a need for further testing — or even redesign. The latter is a rare event, but occasionally we encounter it. As you may know, the Saturn I has had thirteen flights, all without a failure. On one flight, one of the first stage's eight engines was cut off early because of improper operation. Since the Saturn has "engine out" capability, the mission was not affected. Instrumentation, however, was essential in pin-pointing the sequence of events. In many cases instrumentation data may offer evidence that some flight environment is not as severe as had been predicted. Possible direct results of this information are reduction of cost and increase in payload mass.

A few of the measurements are quite simple off-on switch positions. A few are measured with very complex instruments; for example, the liquid-vapor "quality" meter, which determines the ratio of hydrogen vapor to hydrogen liquid by nucleonic means. Many of the measurements are made with instruments whose principles are familiar to most of us — thermocouples, resistance thermometers, Bourdon-tube and diaphram pressure gages, piezoelectric vibration pickups, turbine flow meters, capacitive liquid-level probes, hot-wire anemometers, etc. The differences are that these instruments must survive in rather severe environments, their electrical outputs must be compatible with the telemetry systems, they may be measuring phenomena in unusual ranges, and they must have high reliability.

Electrical adaptation of a transducer's output to the telemetry system often requires the use of a "signal conditioner."(4) The signal conditioner may contain an amplifier, power supply, Wheatstone bridge circuits, voltage limiters, and means for automatic pre-flight checkout. Figure Seven is a block diagram of the overall system for a typical stage. On this block diagram it can be seen that some transducers have outputs which do not require signal conditioning. The telemetry systems mentioned are the pulse coded modulation (PCM) system, which is digital in nature, the single-sideband (SS) system for wide-band data such as vibration and acoustic, and the frequency modulation (FM) system for low frequency analog data. Also shown on the diagram are the pre-flight checkout provisions which use commands to the signal conditioners via remote automatic checkout system (RACS) and data from the PCM telemetry via coaxial cables. The latter is a data collection system called the digital data acquisition system (DDAS). By means of the RACS and DDAS the entire measuring system for the Saturn vehicle can be checked out rapidly and automatically. A computer usually performs this function.

Almost half the flight measurements made on Saturn are of temperature or pressure. We have concentrated considerable attention toward the development of reliable, but inexpensively mass-produced temperature and pressure transducers. Most temperature measurements are accomplished with either thermocouples or resistance thermometers. A few thermistors are used for measurements over very small spans — such as a total change of 10°C, for example. Thermocouples used in the laboratory usually require ice baths for the reference junctions. In industrial applications, the recording instrument usually employs an electrical or mechanical compensation for the reference junctions' temperature. In the case of rocket vehicles, we solved this problem with a simple, inexpensive, and tiny electrical compensation device. It has permitted the widespread use of inexpensive thermocouples. For pressure measurements, we chose the potentiometer-output transducer when accuracy and time response requirements permitted. This instrument uses a Bourdon tube, diaphram, or bellows to activate a mechanical linkage to the moving contact of an electrical potentiometer. The electrical output from a potentiometer does not require amplification, so the expense of a signal conditioner is avoided.

Temperature and pressure measurements are made throughout the Saturn vehicles. Typical areas monitored include the engines and other parts of the propulsion system, the structure, the propellant systems, and the guidance and control systems.

Other measurements include vibration, strain, flow rate, liquid level, acceleration, and electrical parameters.

A majority of the flight measurements require an overall accuracy of ±5% of full scale range. A few special cases require higher accuracy; for example, ±0.1% accuracy has been needed (and obtained) for some engine combustion chamber pressure measurements. These figures include transducer, signal conditioner, telemetry, recording, and evaluation errors. The RACS is scaled to assure these accuracies.

Environmental conditions during a vehicle's flight could lead to instrumentation failures if we had not designed equipment to survive. Electronic equipment can usually be protected from extremes of temperature, and is, therefore, normally subjected to conditions between -20 and +70 degrees Celsius. Temperature transducers must withstand the environments they monitor, of course. These range from the temperature of liquid hydrogen, -253°C, to over 1600°C (in one case to 2800°C). Rocket vehicles are notorious for vibration and acoustic pressure because of the operation of the engines and the aerodynamic behavior. A typical environment would involve oscillating vibration levels of plus and minus fifteen times the acceleration due to earth's gravity and sound pressure levels of 150 decibels above a reference level of one dyne per square centimeter (reference is normal threshold of hearing).

Some typical transducers are shown in Figure Eight. From left to right, they are: a calorimeter (to measure heat flux), a thermocouple, a thermocouple reference junction, two pressure transducers, two liquid level detectors, and a flowmeter with its internal turbine removed. Components of a signal conditioning system are shown in Figure Nine.

CALIBRATION DATA

Of particular interest to this conference might be the calibration facilities. Each stage contractor has a standards laboratory with standards certified by the National Bureau of Standards, and calibration facilities which are geared to mass production, but whose standards are maintained by the standards laboratory. A similar situation exists at MSFC. Figures Ten, Eleven, and Twelve show, respectively, the MSFC facilities for calibration of flight pressure transducers, cryogenic flowmeters, and signal conditioners used for temperature measurements. Calibration data on each measurement's transducer and signal conditioner are recorded on magnetic tape in digital form. The mathematical equation of each calibration curve is derived from these data by a computer and stored. During post-flight evaluation these stored equations, plus the ground station recordings of flight data, are used by computers to print out the flight time history of each measurement in both numerical tables and analog graphs. The tables and graphs are in engineering units, such as degrees Celsius, versus flight time in seconds. Figure Thirteen shows a typical analog chart produced by a Stromberg-Carlson 4020 computer. The example chosen shows the time history of a temperature measurement made during the flight of an uprated Saturn I.

PREFERRED UNITS

Since July 1963, the officially preferred system of units at Marshall Space Flight Center has been the International System (Systeme International d'Unites or SI). It is also the preferred system at several other NASA centers. However, its use is not mandatory. Some NASA centers had become too involved with the English system to permit an inexpensive change-over. Even MSFC is not completely converted, and several of the Saturn stage contractors give their flight measurement calibration data in English units. Fortunately, the computer is non-discriminatory and is willing to print out data in either or both systems. The final Saturn flight evaluation reports are in International System units.

As you might expect, there has been some confusion in the rocket business due to the mixed systems of units. Probably the worst mistake was in mixing absolute and gravitational units.(5) This led to the specification of rocket engine performance in improper units. Specific impulse (I_{sp}) is the engine thrust in force units divided by the rate of propellant consumption in units of mass per interval of time.

$$I_{sp} = \frac{F}{m/t}$$

Unfortunately, it has been customary to give thrust in pounds force, and propellant consumption in pounds mass per second. The early workers erroneously cancelled the pounds in the numerator and denominator and ended up with I_{sp} in seconds. Simple dimensional analysis will reveal that the correct units are identical with velocity units. This error is so deeply entrenched in the rocket field that even modern workers who know better use "seconds" to describe the performance of rocket engines. It was to avoid errors like this that NASA decided to standardize on <u>one</u> preferred system of units.

FUTURE OF SPACE MEASUREMENTS

The operational Saturn vehicles, that is, the ones that carry astronauts or other payload, will continue to carry a number of measuring instruments which will have their data telemetered to the ground. However, referring back to Figures Five and Six, we note that the quantities are greatly reduced. This is because the basic development of the vehicles will have been completed. This is already the case for the uprated Saturn I. Any new developments in the technology of launch vehicles, such as development of a nuclear stage, would require the inclusion of new measurements.

To return to the theme of discovery of new information from space, we can expect the technological and scientific experiments to use measurements in great number. The manned lunar landing program established as a national goal in 1961 has made available the space vehicles necessary to the large-scale exploration (measurement) of the heavenly — and earthly — phenomena. Many experiments will be conducted by the Apollo Applications Program (AAP).

A few examples of AAP experiments may serve to indicate the scope of this important program. The Apollo Telescope Mount (ATM) is a modification of the Lunar Module (LM) or "Bug," which will provide a group of solar observation instruments.(6) These experiments will concentrate on observations in that part of the spectrum not observable in the earth's atmosphere; for example, ultra-violet and X-rays. Figure Fourteen is an artist's concept of this experiment. Some data will be brought back on photographic film by the astronauts; other data will be telemetered.

Other AAP experiments of interest because of their measuring techniques, are those dealing with meteorology and surveys of the earth's resources. In these cases, the astronauts will turn their measuring eyes back toward the earth. The results of these measurements could have far-reaching effects on the daily lives of the world's inhabitants. Through techniques commonly called "remote sensing," valuable data on weather, agriculture, forestry, geography, cartography, geology, oceanography, air and water pollution, and even urban planning can be gathered economically.(7) (8) The prospects of using such techniques just for the single objective of aiding in world food production are quite exciting.(9) During the growing season, ability to identify healthy and unhealthy crops and soil conditions would greatly aid farmers and agriculture planners.

Measurement technology, so important to man's rise in civilization, continues to play a major role as man enters space. Those of us who work in the measuring field may well take pride in the future applications of our technology to the benefit of mankind. Perhaps we will do our part to fulfill the admonition of the twenty-fifth chapter of Deuteronomy:

> "....A perfect and just measure shalt thou have:
> that thy days may be lengthened in the land which
> the Lord thy God giveth thee."

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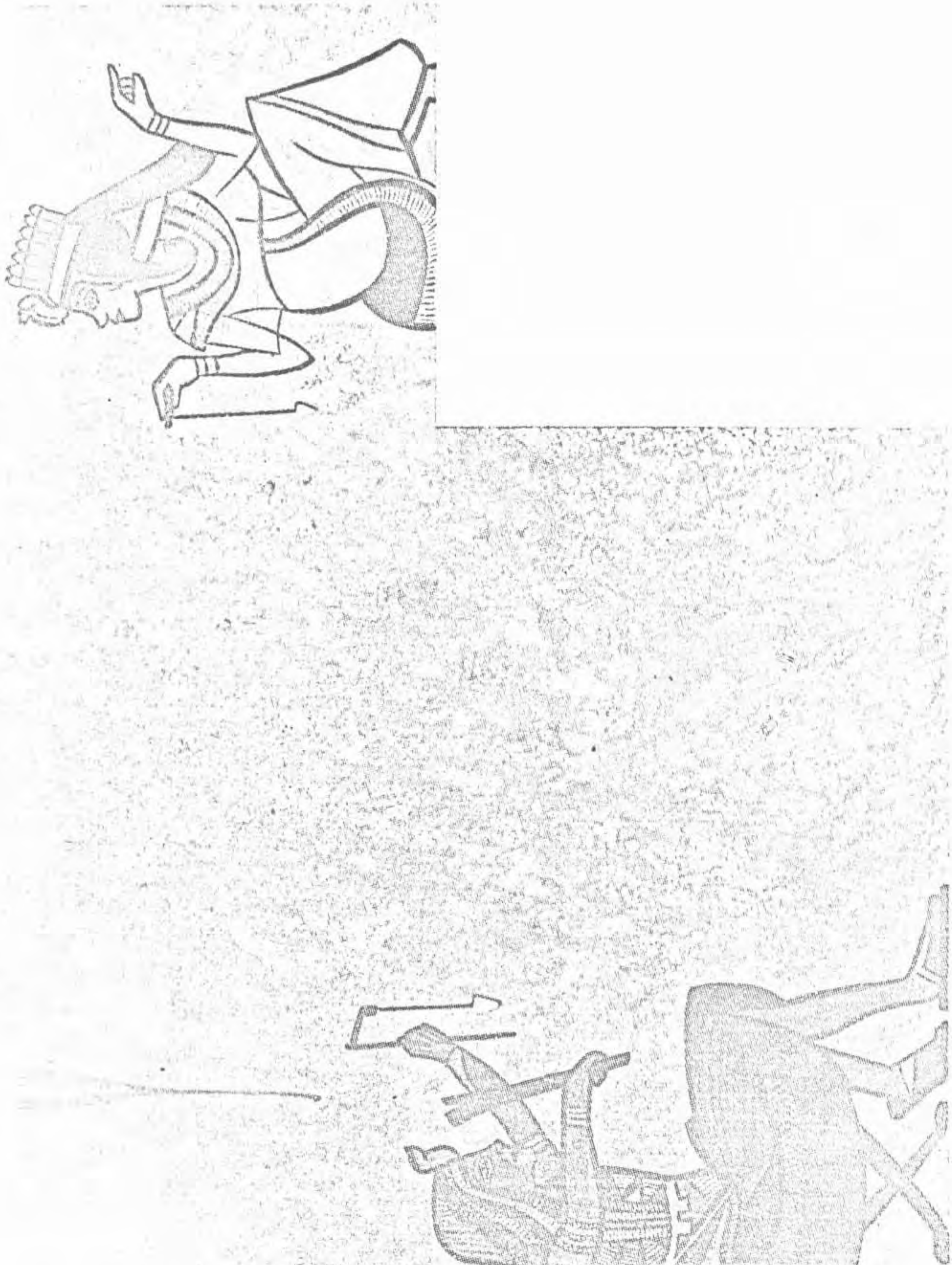
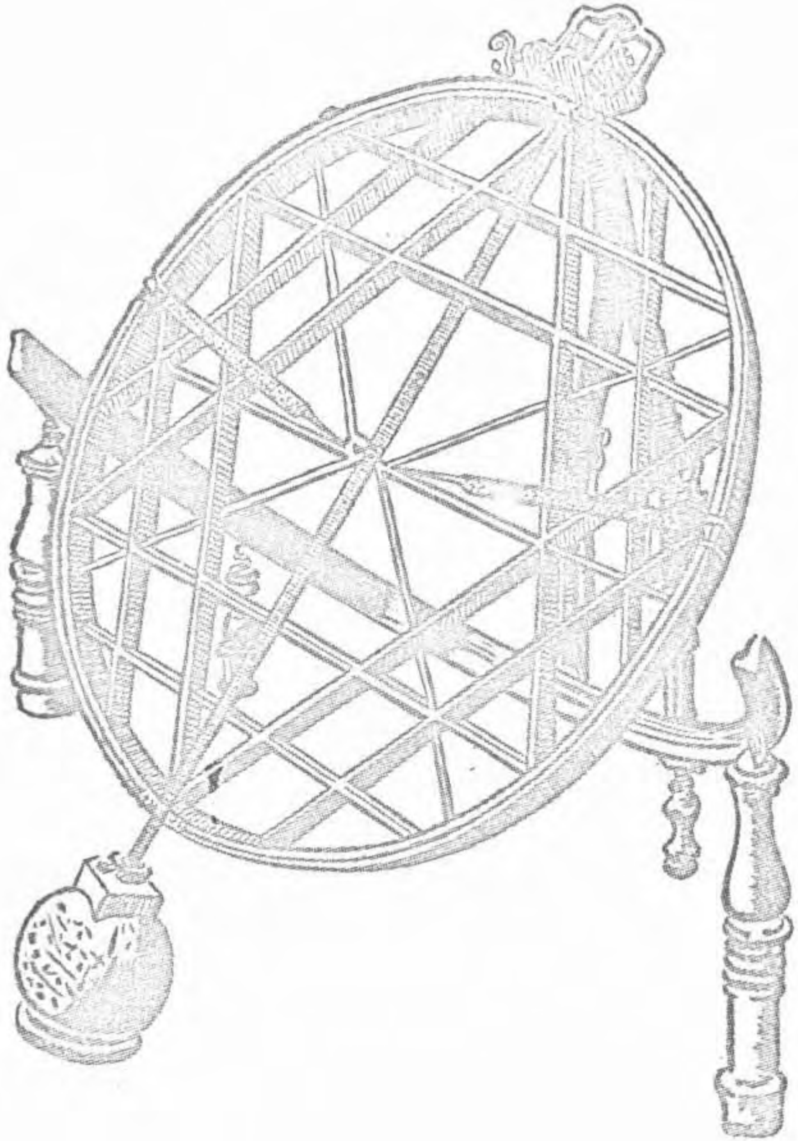
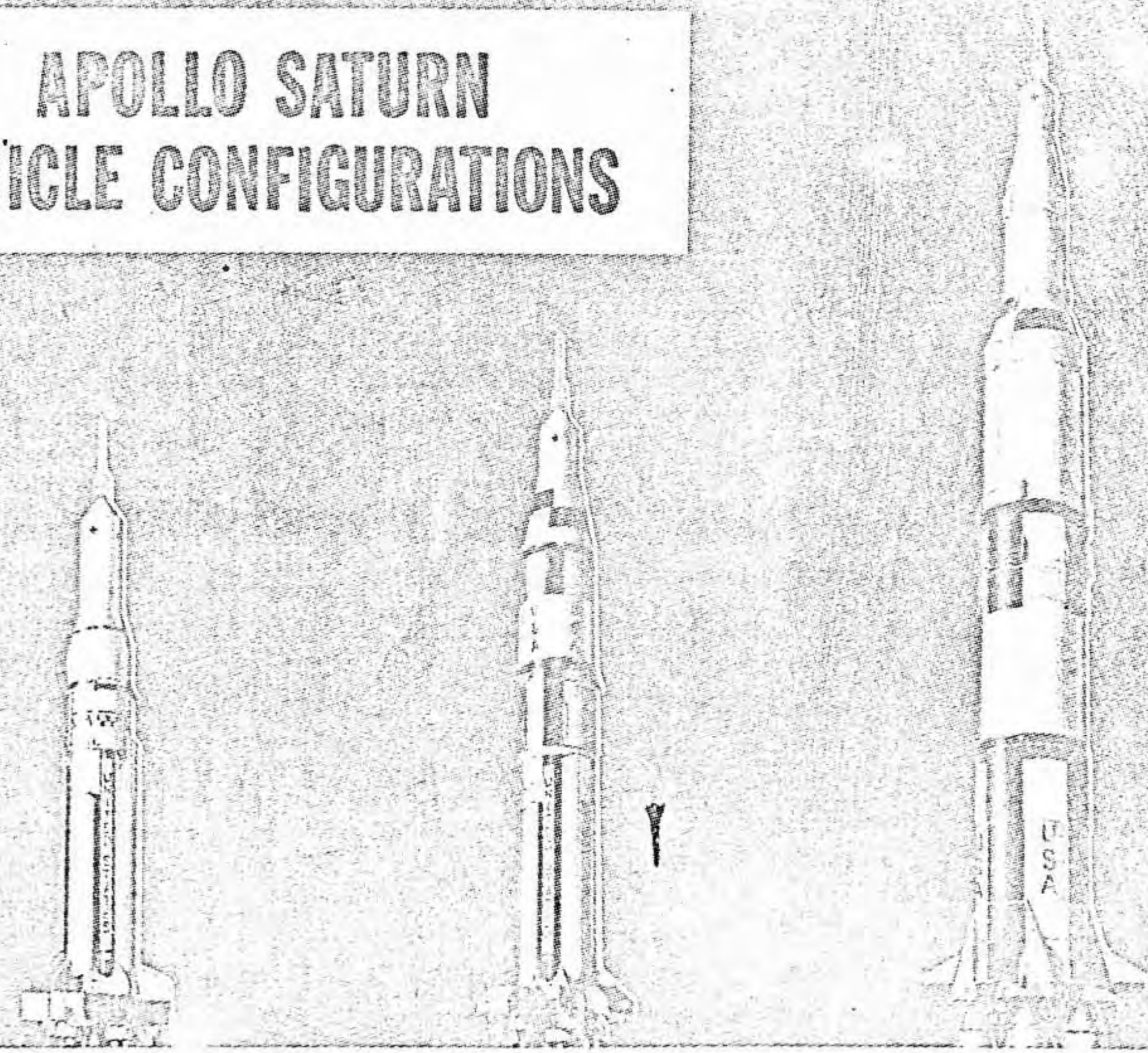
ILLUSTRATIONS





APOLLO SATURN VEHICLE CONFIGURATIONS



SATURN I

UPRATED SATURN I

SATURN V

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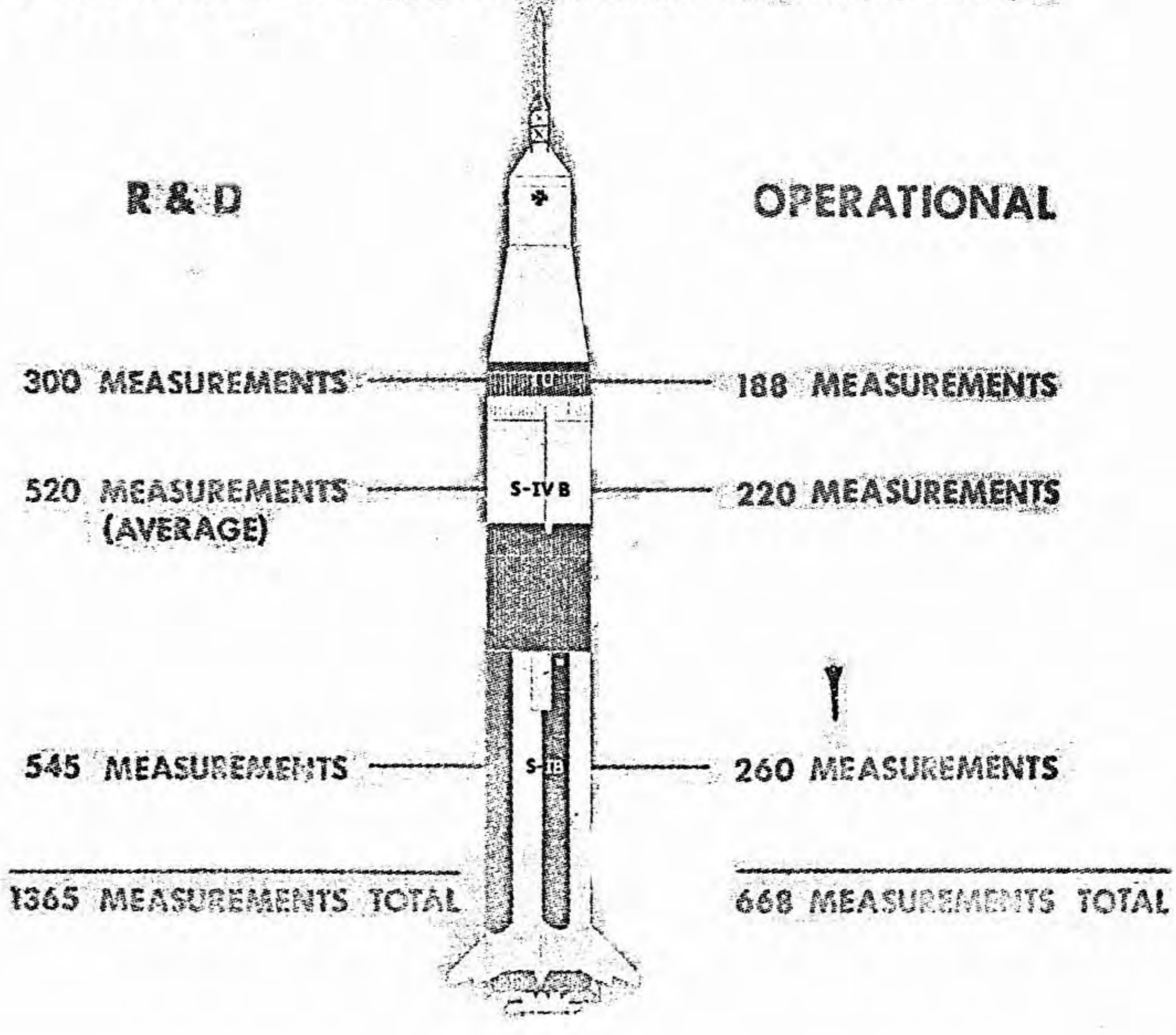
UPRATED SATURN I/ INSTRUMENTATION



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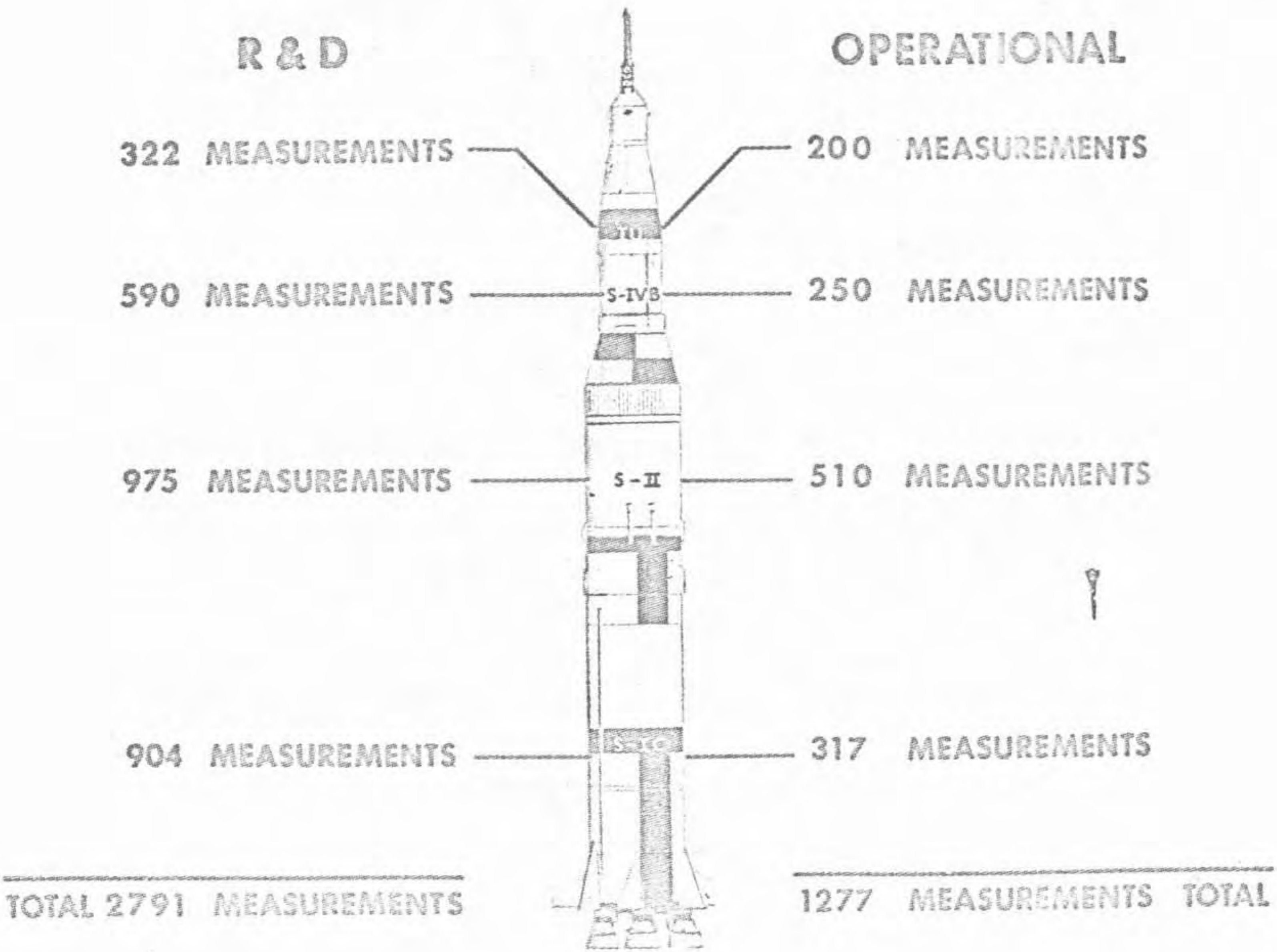
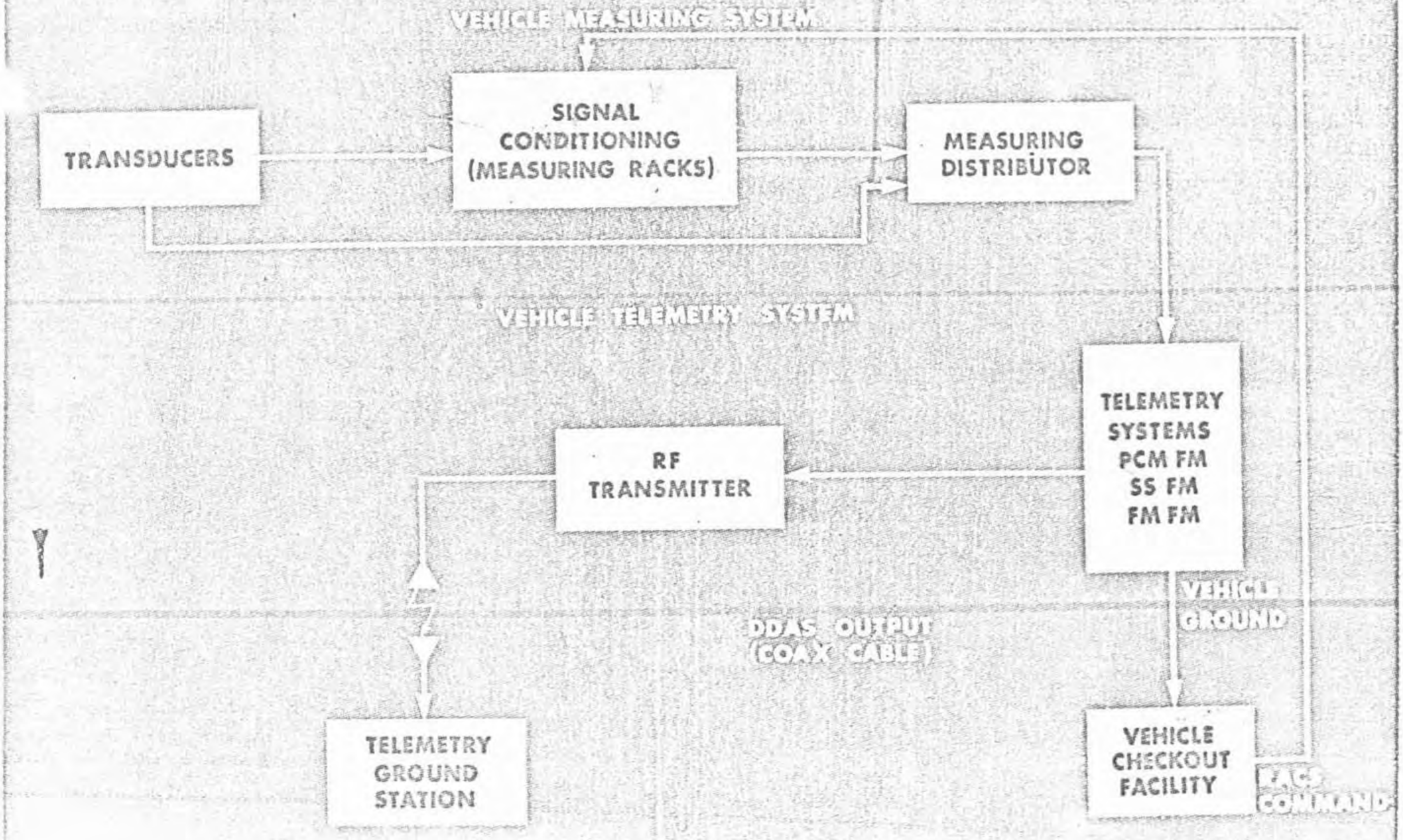
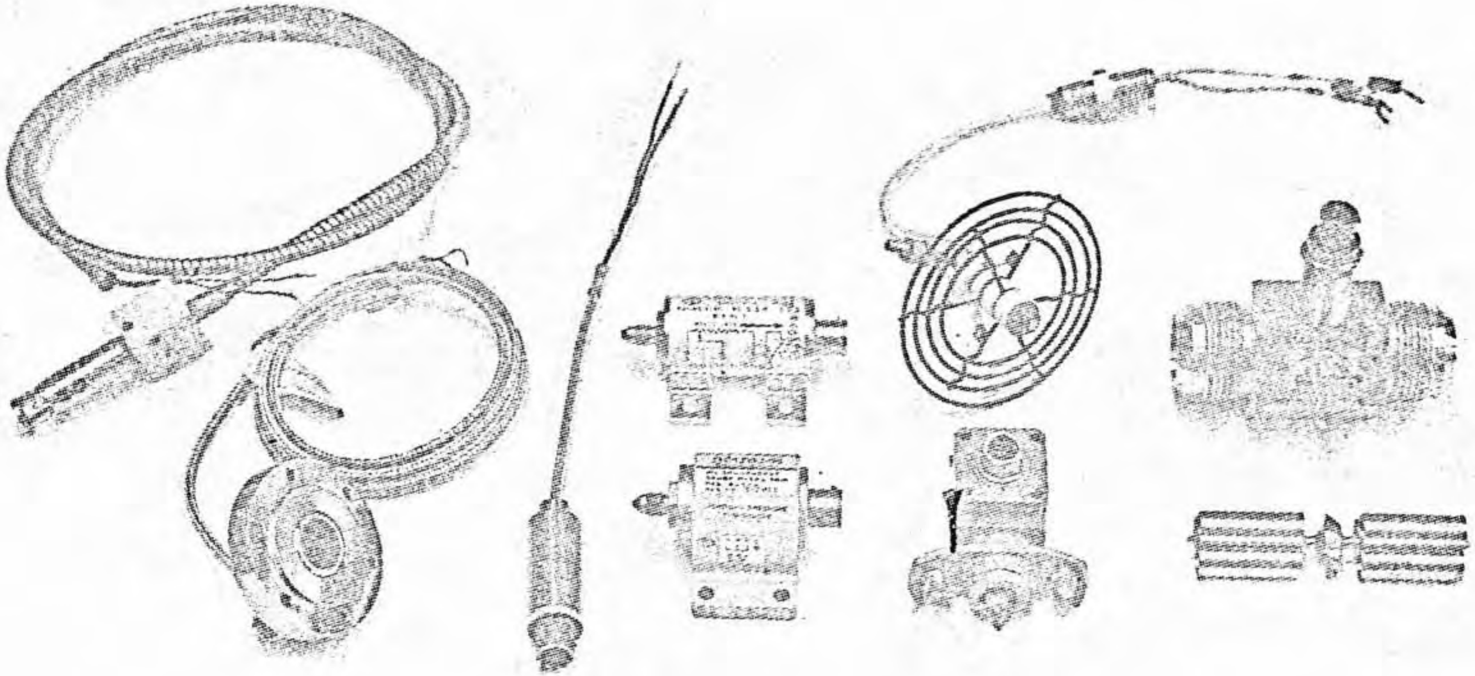
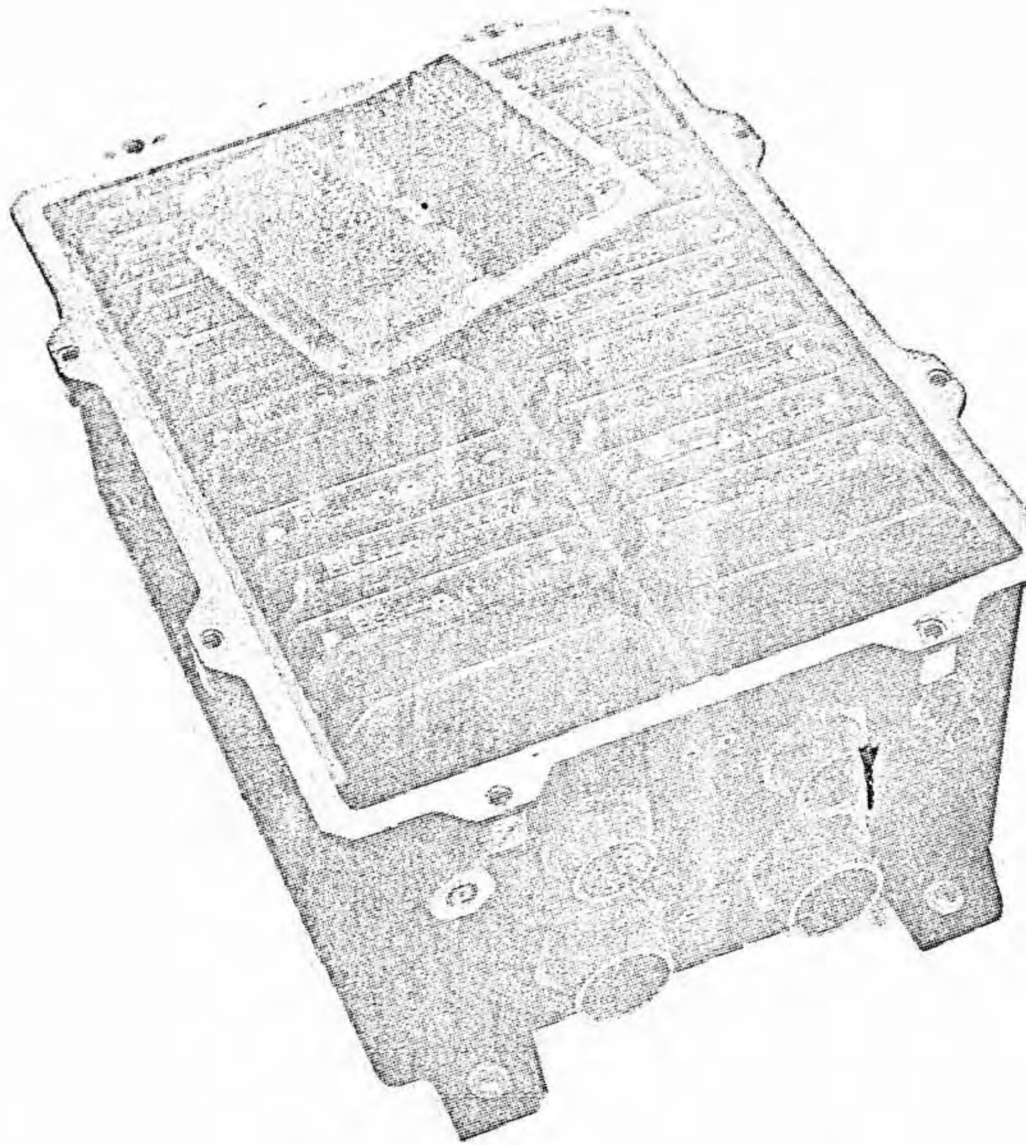
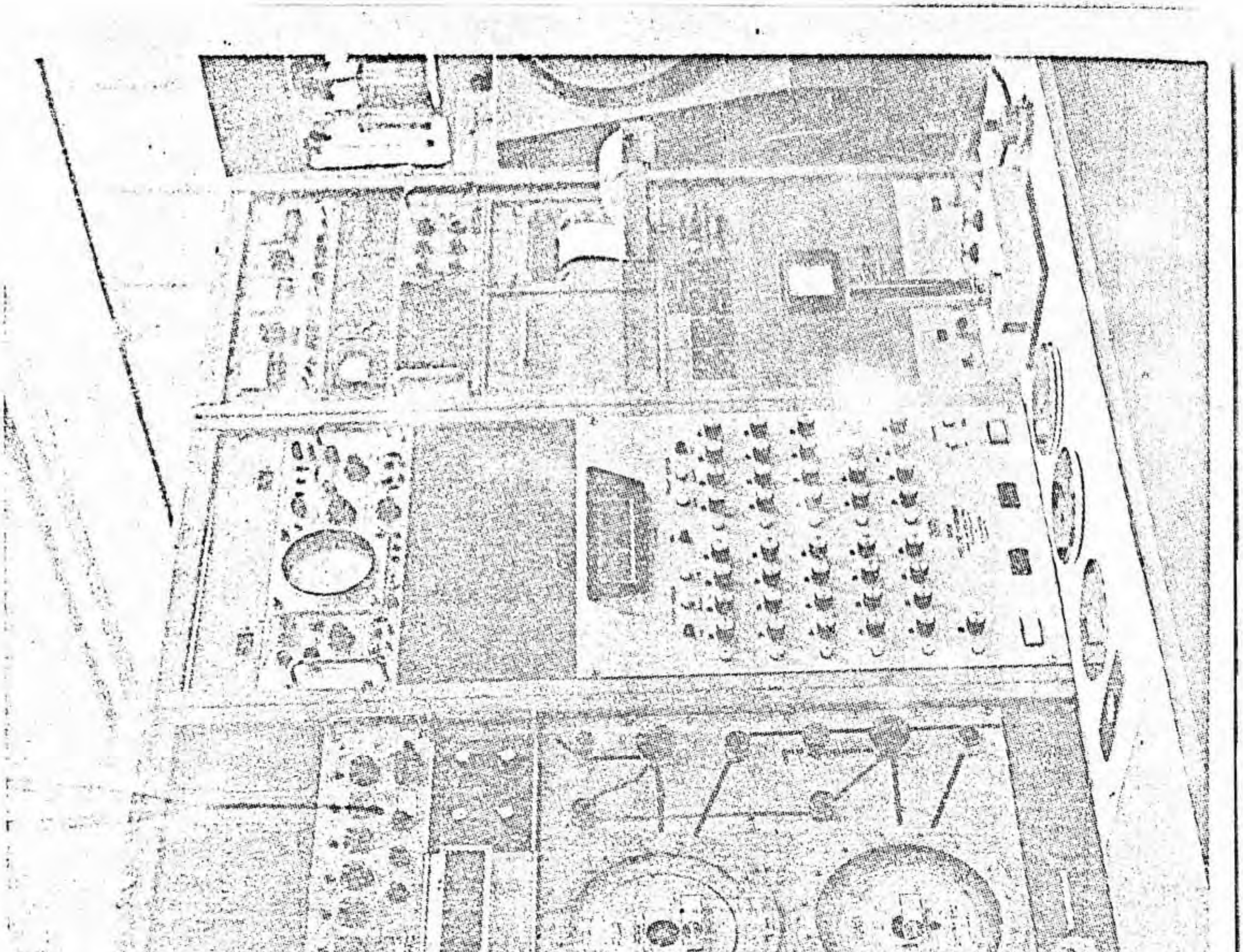


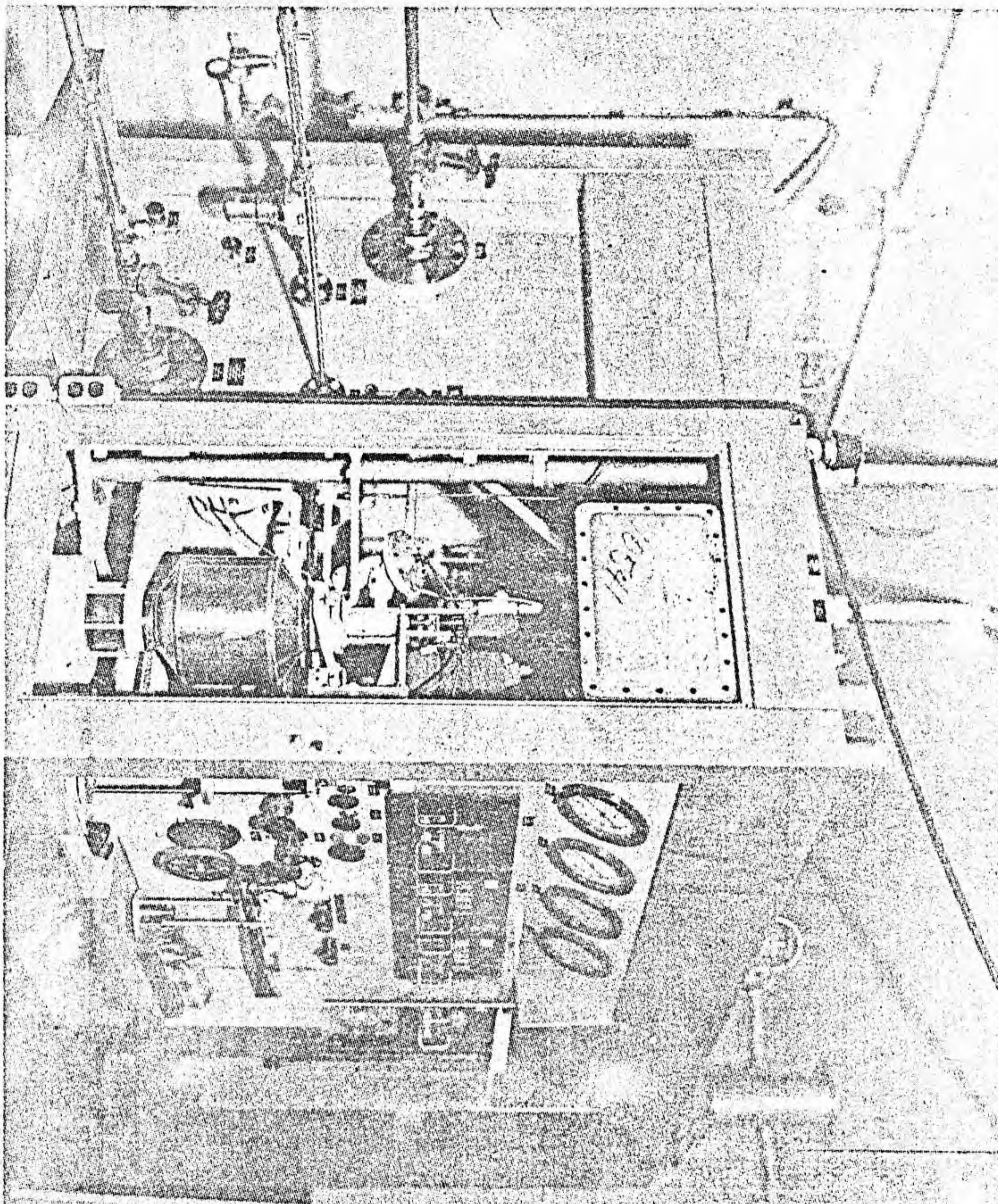
TYPICAL SATURN STAGE INSTRUMENTATION SYSTEM

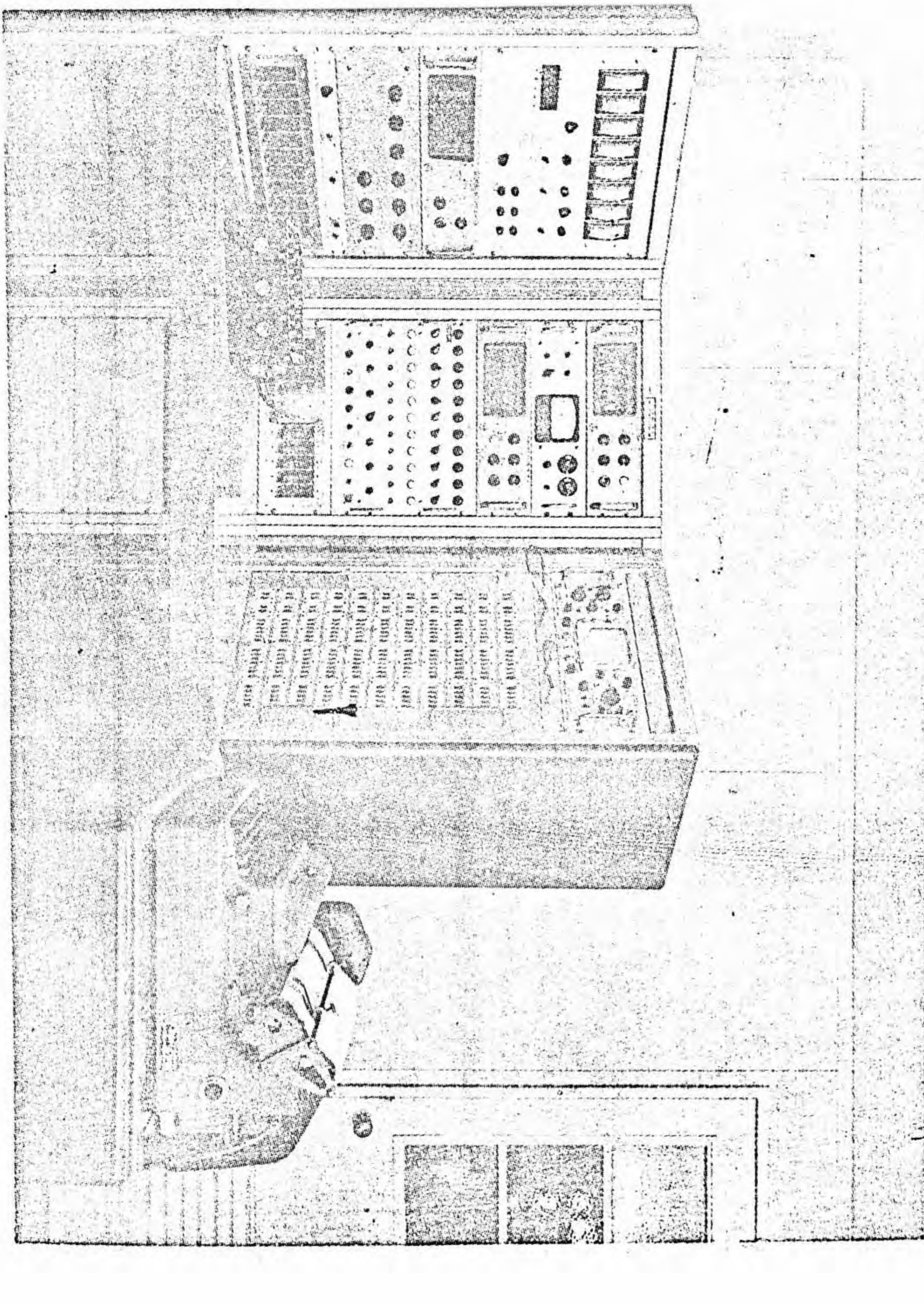


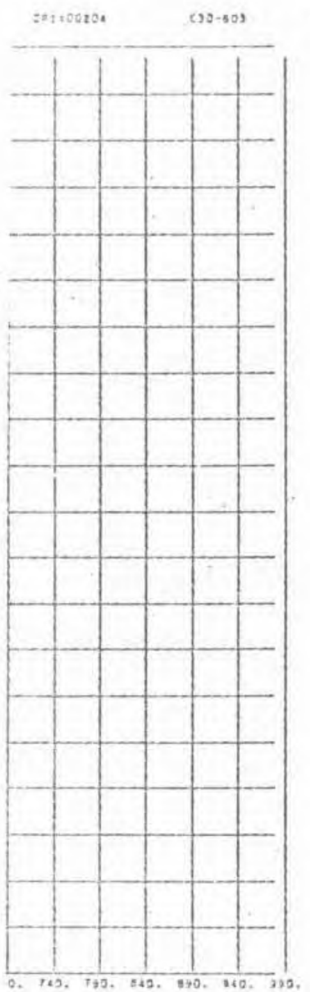








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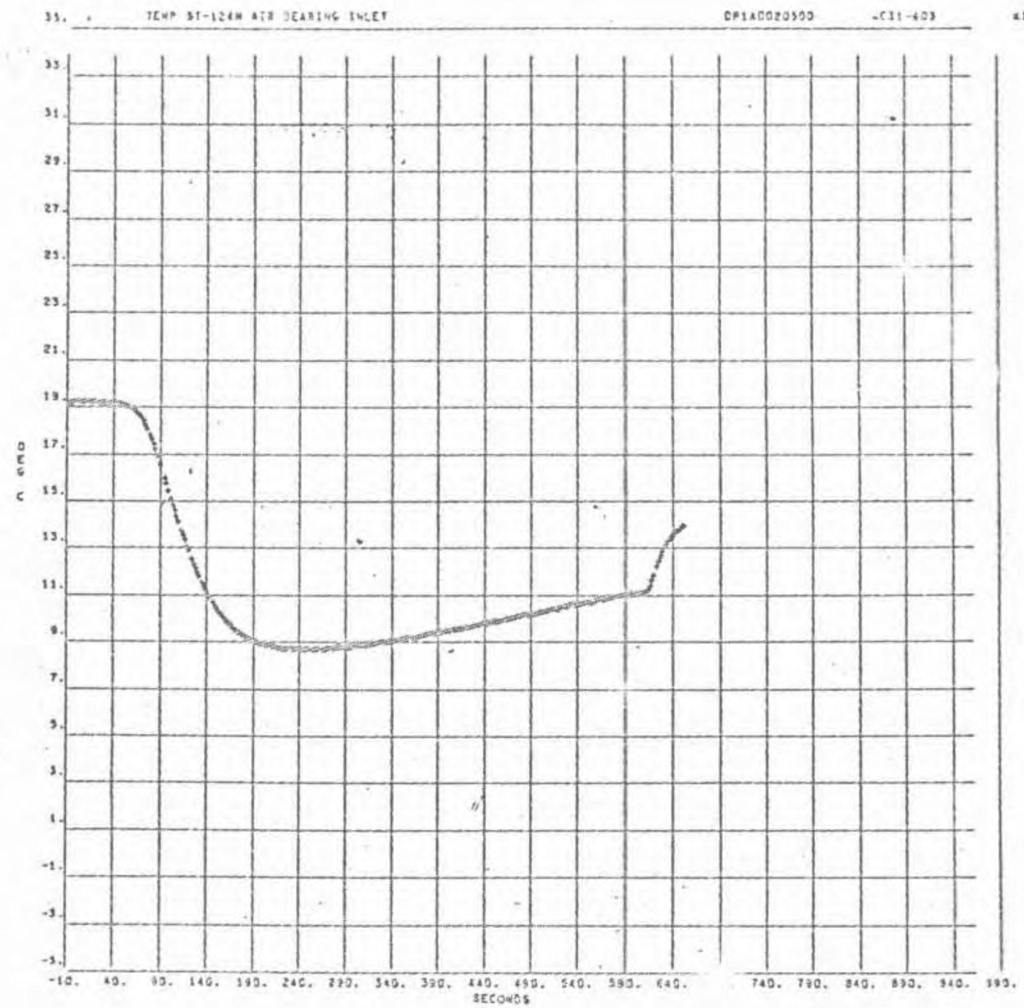
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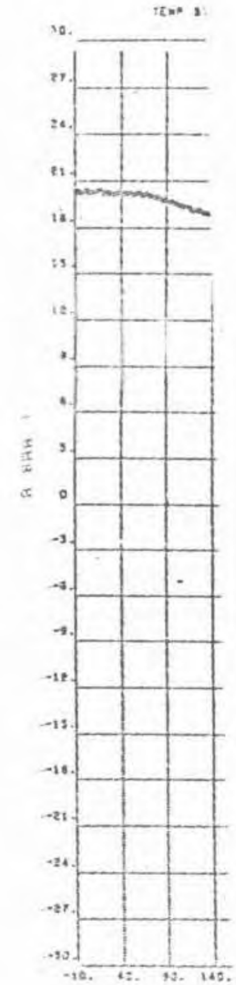
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